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Road pricing strategies for the greater Oslo area

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Summary:
Road pricing can produce substantial efficiency gains, but high and low income groups will be affected differently. This report describes the construction and application of a modelling framework to analyse both efficiency and equity impacts of selected first- and second best road pricing strategies in the greater Oslo area of Norway, and report results. The strategies considered differ with respect to the road pricing measures that are available (traditional vs link-based measures), whether only short-term or also medium-term effects are considered, and with respect to redistribution and use of the revenue. In conclusion, there are trade-offs between the three aspects of road pricing – efficiency in the transport sector, efficiency of the tax system and equity. For a successful implementation of road pricing, these tradeoffs must be studied carefully in each particular instance.

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Sammendrag:
Vegprising kan å øke den totale økonomiske effektiviteten i samfunnet, men kan samtidig bidra til at forskjellige inntektsgrupper berøres ulikt. Denne rapporten beskriver oppbygning og anvendelse av et modellsystem for analyse av både effektivitet og fordelingsvirkninger for noen optimale vegprisingstrategier i Oslo og Akershus, og gjennomgår resultatene. Strategiene skiller seg fra hverandre ved hvilke virkemidler som er tilgjengelig for vegprising (tradisjonelle versus lenkebaserte virkemidler), hvorvidt bare kortsiktige eller også middels langsiktige effekter tas i betraktning, og på hvilken måte provenyet fra vegprisingen tilbakebetales i form av skatte-lette. Analysene viser at det er en avveining mellom tre aspekter ved vegprising – effektivitet i transport sektoren, effektivitet i avgiftssystemet og fordelingsvirkningen. For en vellykket implementering av vegprising må disse avveininger studeres i hvert enkelt tilfelle.

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Preface

As a part of the AFFORD project, the Institute of Transport Economics (TØI) has studied efficiency and equity effects of road pricing in the Oslo region. AFFORD was funded by the European Commission under the Fourth Framework Programme. It was carried out by a consortium led by VATT, Finland. Participants were VATT, ITS, UPM, TOI, TUD, TRIAS, MIP, UYORK, LTCON, C.I.S.R, FUA. National funding for the Norwegian work was granted by the Norwegian Research Counsil through its LOKTRA programme. Additional funding at the final stages was provided by Opplysningsrådet for veitrafikken.

The present report is not formally a part of the documentation of the AFFORD project. However, it can be seen as a report on the Oslo case study in that project, providing details on the methodology as well as a more comprehensive overview of the results published (together with results from Helsinki and Edinburgh) in Deliverable 2A of the AFFORD project. Although we take full responsibility for any errors in the Oslo study, we are indebted to the partners of the AFFORD consortium for their valuable suggestions and numerous discussions. We also want to thank those who funded the project.

To an equal degree, this report is also a product of the Strategic Institute Programme on cost benefit analysis of transport strategies and summarises some of the methodological findings in that programme: Urban marginal cost pricing strategies can be identified by optimisation with a transport model. Spatial equity analysis of these strategies can be performed by utilising the disaggregated nature of the transport model. The Strategic Institute Programme was funded by the Norwegian Research Council under the LOGITRANS programme and internally by TØI.

The report was written jointly by the three authors. We greatly thank Peter Christensen for fruitful comments on parts of the manuscript. Laila Aastorp Andersen has provided secretarial assistance.

Oslo, March 2001
INSTITUTE OF TRANSPORT ECONOMICS

Knut Østmoe
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Head of Department

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Summary:

Road pricing strategies for the greater Oslo area

Background

Due to increases in household car ownership rates, demographic changes and changes in the geographical patterns of housing, work and leisure activities, urban road networks are getting increasingly congested in cities all over the world. This entails not only time losses to private and business transport, but also severe noise and pollution problems and degradation of the quality of life in the city centre and surrounding neighbourhoods. For 40 years now, economists have advocated road pricing as a solution to these problems, but somehow the idea seems difficult to get across to the public, and almost impossible to implement in practice. During this time, major road capacity expansion schemes have been carried out in some cities to relieve the problems. However, road transport is still rapidly increasing and congestion is returning as a problem.

In Oslo, a toll ring was erected in 1990 to help finance a road network expansion plan for the urban area. Although much of the plan has already been implemented, congestion is expected to continue. The toll ring will cease operation in 2007, according to current plans. Further plans to relieve the situation is seen as necessary, and differentiated charges by time of day at the toll ring is an option.

Purpose

The purpose of this report is to make a contribution to the implementation of efficient and equitable road pricing strategies in urban areas. Two rather different paths are pursued to this end.

On the one hand, we want to show by a detailed example that it is possible to identify optimal road pricing strategies with the use of a fairly standard transport model and an appropriate optimisation technique, and to study the efficiency gains and distributional issues arising from these strategies by way of cost benefit analysis and a spatial equity analysis. By doing this, we want to invite more studies of a similar nature – and hopefully to solve some of the remaining problems that we have encountered. There is still a lot to be learnt about marginal cost pricing by such studies. Naturally, this purpose entails the need to be fairly technical. The most technical parts of the report are chapters 3-6.

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On the other hand, we want to disseminate our findings from the analyses we have performed for the Oslo region, because we think they merit broad discussion among planners and decision-makers. These results are set out and discussed in chapter 7 and 8. Even these chapters are however not entirely non-technical, we have to admit.

Policy conclusions

The following main conclusions were drawn from our study of first-best and second-best road pricing strategies for Oslo and Akershus:

- Marginal cost road pricing based on available instruments (including the present location of the Oslo toll ring) can produce significant or even substantial economic benefits.
- The benefits do to a large extent depend on the value of the shadow price of public funds, which again depends on whether taxpayers' money is a particularly valuable resource, and whether transport taxes have less distortionary effects than other taxes. If this is the case in the Oslo region, then road pricing is above all an efficient form of taxation. Therefore, the actual distortionary effects of transport taxes merit further study.
- Road pricing produces significant environmental benefits.
- In the conditions prevailing in the Oslo region, travellers' time gains from road pricing are always less than their monetary loss. Consequently, travellers as a group stand to lose by road pricing unless the revenue in one way or another is distributed back to them (e.g. in the form of income tax cuts, lump-sum payments or the provision of a public good for which there is sufficient willingness-to-pay).
- The revenue is usually high enough to allow full compensation to travellers. Road pricing, when coupled to such a recycling scheme, could then be a Pareto improvement. (This statement is subject to the qualification that the effects of the redistributed income on travel decisions have not been studied.)
- Prior to redistribution, road pricing has slightly unfavourable equity effects, as the costs borne by low-income groups will be a proportionally higher share of their household income.
- If, however, the revenue is redistributed to the households in a way that gives approximately the same amount of money to every household, then the negative distributional effects will be reversed, and a more equitable income distribution is achieved.
- According to our calculations, road pricing does not lead to a greater loss of mobility in the low income groups than in the other groups – rather the opposite. There are no indications that the less affluent travellers are priced off, while the rich pay their way. This can probably be explained by the fact that the high-income groups have a higher travel frequency, especially by car during the rush hours, and are therefore harder hit by high peak toll charges.

- Road pricing entails a sharp conflict between efficiency and equity objectives. If the revenue is redistributed so as to improve the income distribution, road pricing will not contribute to improve the efficiency of the tax system. Thus there will be no "double dividend". If, on the other hand, the revenue is used to cut marginal taxes on labour, or used to produce a public good for which there is a high willingness-to-pay, there *will* probably be a double dividend. But in that case, the initial inequality brought about by road pricing is not counteracted.
- Marginal cost road pricing will lead to a significant mode shift from car to public transport in the high-income groups. Even walking and cycling is expected to increase significantly. The health effects of this, consisting of the benefits of physical activity and improved air, and the costs of more accidents, merit future study.
- Assuming a shadow price of public funds of 0,25, and toll charges and parking charges as available instruments, the optimal toll charge in rush hours becomes approximately 4.0 Euro (4.2 times the current level of 0.95 Euro) in Oslo. The optimal toll charge in the off-peak period becomes 2.7 times the current level.
- These charges generate a revenue capable of reducing the municipal income tax in Oslo and Akershus by 1,7 percent units, or to allow a lump-sum transfer to each household of approximately 290 Euros per year.
- Assuming a zero shadow price of public funds, the optimal toll charge in the rush hours becomes about 2,7 times the current level, whereas crossing in off-peak periods should be free. In this case, the revenue is significantly lower, corresponding to 0,3 percent of gross income or 57 Euros per household per year.
- Assuming that the fuel tax could be used as a local instrument, the optimal fuel tax in Oslo and Akershus under the assumption of a shadow price of public funds of 0.25 would be twice the current level. In this case, there are less need for high toll charges: 3.5 times the current level in rush hours and 2.3 times the current level in off-peak periods.
- This policy would generate a revenue sufficient to reduce the income tax by 4 percent of gross income, or to give to each household in Oslo and Akershus a sum of 679 Euros per year.
- Although these effects are substantial, only a fraction of the theoretically achievable welfare effects are reaped by marginal cost road pricing at the present toll ring. There is a case for considering slightly more advanced forms of road pricing, including a more favourable location of the ring or a system consisting of several rings.

Commercial traffic has only been treated in a very crude way in this study.

Some methodological issues

The shadow price of public funds

Road pricing is, among other things, a form of taxation. Generally, taxes create inefficient allocations in the economy because they drive a wedge between the marginal cost of production and the price the consumer has to pay. The seriousness of this problem differs however between the different kinds of taxes. Too little is known about how transport taxes perform in this respect.

The inefficiency loss to the economy as a whole when an additional Norwegian krone (NOK) of public funds is raised by raising all existing taxes proportionally is called *the shadow price of public funds*. For Norwegian cost benefit analyses, it is officially recommended to use a shadow price of public funds of 0.20, meaning that for each additional krone that will have to be raised by taxation, the economy will suffer a loss of 0.20 (or conversely, each taxpayers' krone saved contributes 0.20 to the economy).

Road pricing strategies inevitably produce a large revenue for the government. The social value of this effect depends on the following factors:

1. Does road pricing itself produce distortionary effects in the economy outside of the transport sector?
2. How is the revenue used? Is it used to cut back the most distortionary forms of taxation (like the tax on labour) or to provide a public good for which there is a high willingness-to-pay, or is it used for other purposes than to improve the efficiency of the economy?

If road pricing – or transport taxes in general – have much less distortionary effects than the labour tax, and if the revenue is used to improve the efficiency of the economy, then there is a case for valuing the revenue at a rate of say 1.20 or 1.25 per krone. Since we know so little about the distortionary effects of transport taxes, all our analyses have been performed under the two different assumptions of a shadow price of public funds of 0.00 and 0.25. The first assumption covers the cases where transport taxes are just as distortionary as other taxes, and even the cases where they are not, but the revenue is used for other purposes than to improve efficiency. The second assumption covers the case where transport taxes are efficient forms of taxation and the revenue is used to cut back inefficient forms.

Furthermore, we have assumed that if the purpose of revenue recycling is to counteract the adverse distributional effects of road pricing, the efficiency of the tax system will not be improved. So for these cases, a zero shadow price of public funds is used to value the revenue from road pricing. Conversely, a 1.25 shadow price is used when no measures are taken to improve the income distribution. Under these plausible assumptions, there is a potential conflict between efficiency and equity objectives. Our analyses show that this conflict is in fact quite acute.

A spatial equity analysis

In the equity analysis, the population of the urban areas is divided by household income per consumption unit into eight equally-sized income brackets. However, the gains and losses that a particular income group gets from a particular road pricing strategy depend on where they live. Thus we will have to assess the effects separately for each of the income groups in each of the zones of the urban area. Only after this is done can the results be aggregated to produce the new income distribution in the area as a whole, and to compute measures of inequality.

To perform this spatial equity analysis, we have made use of the disaggregate nature of the transport model and its underlying empirical data. From the empirical sample, synthetic zonal populations, resembling the real populations as closely as possible with respect to the income distribution, have been constructed. This "prototypical sample" technique of constructing the transport model permits us to compute benefits and gains for each income group in each of the zones.

Optimisation

The base case is the mid-nineties situation in Oslo, except that the charges at the toll ring are set to zero. A social efficiency objective function is used to assess the benefits and costs of each pricing strategy relative to the base case. It consists of benefits and costs to travellers, operators, the government and the environment. To compute value of the objective function for a given pricing strategy, the pricing strategy is implemented in the transport model, and the transport model output is used to compute the social efficiency of the strategy.

It is well known that social efficiency is maximised if and only if prices are set equal to marginal social costs. Thus if we are able to find the maximum point of the social efficiency objective function, the corresponding prices should be marginal cost prices. The whole purpose of road pricing is to maximise social efficiency by letting travellers face – as closely as possible – the marginal social costs that their choices imply.

Two different techniques are used to optimise the social efficiency objective function. They correspond to the cases of "first-best" and "second-best" pricing respectively. In first-best road pricing, all links in the road network can be charged. Since this is an awful lot of policy instruments, we must make use of what we know about the structure of charges in the optimal solution. Such charges are then added to the link cost functions of the network model.

In second-best road pricing, only a few of the links in the network can be charged. In our case, this is the links that cross the toll cordon. Furthermore, the charge must be the same on all these links. (It would however be interesting to study the efficiency and equity implication of relaxing this constraint.) To improve the situation, there might also be some other instruments available, like parking charges, a local fuel tax, public transport fares etc. We do not have the same knowledge about the structure of second-best solutions, but on the other hand, the number of policy instruments are restricted to a manageable handful. This permits another optimisation technique to be used without unreasonable demands on computer resources. (Our computer department may disagree to this statement.)

To facilitate the use of this technique, we have been forced to consider area-wide instruments only. That is, the charges at the toll ring are the same everywhere, as mentioned, and the *relative* changes in parking charges, public transport fares etc. will be the same throughout the area. These simplifications of the second-best policies considered are introduced to keep the demands on computer resources to a minimum, but it may also very well be that they correspond to real constraints on the available policy instruments. A bit of programming on the transport model is essential to allow us to use only one command to make simultaneous percentage changes in transport service levels and charges throughout the networks.

The optimisation technique for second-best pricing consists of a series of transport model runs, following each other automatically according to an algoritm that does not use derivatives (a DUD algoritm), and terminating when the changes from the last run becomes small enough. The Downhill Simplex algoritm was used in our study. Running on a HP9000 (D270) UNIX machine, the optimum solution for a particular scenario was found in approximately 3 days. Thus it seems possible to analyse slightly more complex problems than the ones studied here, allowing for more policy instruments to be included in the strategy, more time periods to be considered simultaneously or more zones in the transport model.

It is of course essential for the analysis of pricing strategies that the model is run to equilibrium (in the network and between supply and demand) at each iteration.

Problems

There will always be unresolved problems. We have tried to point them out for further study in the text and in some cases also in the conclusions. From a technical point of view, the two most troublesome problems we have met are:

1. How should we compute user benefits when the local transport model includes a car ownership model?

The problem is that cars are not only bought for use in the urban area, but also for longer trips, holidays and weekends etc. By definition, these trips are outside our model and so is the benefit derived from them. A pricing policy that affects car ownership is perhaps not to be evaluated in the urban transport markets alone. We have been forced to do so, but the results of optimisation when the car ownership model is included are obviously less trustworthy, and probably altogether useless when car taxes are included as policy instruments.

2. How should we take account of a positive shadow price of public funds in first-best optimisation?

The problem is how to include the benefits of saving taxpayers' money when the link cost functions are modified to make travellers face the real social costs of traversing the link. The theoretical soundness of the actual solution chosen in this study is open to debate.

1 Background

Due to increases in household car ownership rates, demographic changes and changes in the geographical patterns of housing, work and leisure activities, urban road networks are getting increasingly congested in cities all over the world. This entails not only time losses to private and business transport, but also severe noise and pollution problems and degradation of the quality of life in the city centre and surrounding neighbourhoods. For 40 years now, economists have advocated road pricing as a solution to these problems, but somehow the idea seems difficult to get across to the public, and almost impossible to implement in practice. During this time, major road capacity expansion schemes have been carried out in some cities to relieve the problems. However, road transport is still rapidly increasing, capacity is quickly exceeded and congestion is returning as a problem.

In Oslo, a package of road and tunnel projects (Oslopakke 1), financed by the Oslo toll ring and by governmental grants, was implemented from 1990 onwards and is scheduled to be completed by year 2007. It is now seen by more and more people as having only a temporary effect on the problems. Consequently, a package of public transport projects (Oslopakke 2) is currently planned. However, road pricing in the form of charges varying between peak and off-peak at the existing toll ring, or a combination of road pricing and the public transport improvements, are also increasingly seen as options. Legislation to allow for the possibility of road tolling for other purposes than infrastructure building will probably be enacted this year.

Perhaps paradoxically, the new interest in road pricing comes at a time where there is much concern about the level of taxes on motorists in general. There are also widespread worries about the distributional effects of road pricing. In this report, we want to address both the efficiency and equity aspects of road pricing in the Oslo region. Furthermore, we want to address these issues in a broad framework where the effects on public transport and the environment are included.

By *road pricing* we mean any set of pricing measures that induce motorists to make their travel choices taking into account the congestion, environment, accident and road wear costs they impose on others at the particular time and place they are driving. Road pricing can be implemented in a more or less perfect way. Therefore, all of the following measures alone or in combinations can be used for road pricing purposes: (i) Taxes on the purchase and licensing of vehicles and on associated commercial services, (ii) Taxes on the purchase of fuel, (iii) Charges on parking, (iv) Charges on using particular stretches of road, and (v) Time based or kilometre based charges on driving inside a particular area. The first two categories are considered national measures and the three last categories are considered regional measures. The three last categories can also be differentiated by time period. An example of the fourth category is the toll rings in the three Norwegian cities: Oslo, Bergen and Trondheim. An example of (iii) is the local fuel tax in Tromsø.

Marginal cost road pricing may be defined as road pricing where the values of the transport measures that are available to us are set such that social welfare is maximised. Note that in real life, we will never have a situation were all measures we could think of are available to us. One obvious reason for that is the cost of implementation, which is very high for some of the most sophisticated measures. Nevertheless, we call it marginal cost pricing if we use the instruments that we have as efficiently as we can to improve social welfare. Thus road pricing is the broader concept, which does not imply that an optimal level of the instruments are found. Marginal cost road pricing implies an optimal level of the available measures, but the range and scope of our available measures may still be constrained by law, technology or the lack of public acceptance.

The revenue from marginal cost pricing in transport may be used to cut back other taxes, improving the efficiency of the tax system. The efficiency of the tax system is improved because the wedge between marginal costs and consumer prices (or the prices of factors of production) brought about by taxation inevitably reduces the overall social efficiency of the economy.

New taxes and charges in the transport system may affect households differently, depending on their income, location and travel behaviour. If the revenue from the new taxes and charges are recycled to the households, this too may affect households differently, either counteracting or strengthening the initial distributional effects of the new taxes. Equity effects are seen by many as a major obstacle to marginal cost pricing in practice. There is a need to know these effects and to design recycling schemes that counteract them if marginal cost pricing is to win enough support to be implemented in practice. There may also be a trade-off between efficiency and equity involved if recycling cannot be designed without sacrificing the efficiency gains that the introduction of road pricing entails for the tax system as a whole.

The efficiency loss of raising one more NOK[1] of public revenue through the existing tax system is commonly called *the shadow price of public funds*. Estimates of this parameter vary, but it is now officially recommended by the Ministry of Finance to use a value of 0.20 in Norwegian cost benefit analyses. This means that one NOK of taxpayers' money used in a project entails a social cost (a loss in the economy as a whole) of 0.20 NOK. Of course, if the expenditure of the one NOK gives rise to a benefit of 1,20 or more in the transport system, the use of taxpayers' money in the transport sector is nevertheless socially efficient.

If we assume that one NOK of public money raised through road tolls does not have the same distortionary effects in the economy as other taxes, we save 0.20 NOK by substituting road pricing for other taxation. However, this effect vanishes if toll revenue is used for purposes that do not improve the efficiency of the tax system. The implications of this effect for optimal road price levels are therefore crucially depending on how the toll revenue is used.

[1] 1 Euro = appr NOK 8.2

2 The purpose of this study

The main purpose of this study is to find second-best marginal cost prices for the road transport system in the greater Oslo area under different assumptions about which policy instruments are available. We also want to compare the improvement in social efficiency that can be obtained with second-best prices to the improvement that can be obtained with first-best pricing. Finally, we want to study how marginal cost pricing affects equity and the trade-off between the two conflicting objectives of equity and efficiency.

Marginal cost road pricing for the Oslo area have earlier been studied by Larsen and Ramjerdi (1990), Ramjerdi (1995), Larsen and Rekdal (1996), Larsen (1997) and Grue et al (1997). A brief summary of these studies and a discussion and comparison of the results are given in section 8.4. In addition, there are several more studies that describe the present toll ring and its effects on travel behaviour.

Fridstrøm et al (1999) and Fridstrøm et al (2000) have already published many of the results presented in this report. However, the present report gives a more detailed description of the model framework that was used and a more comprehensive and complete presentation of the results.

We develop a framework for cost-benefit analysis of transport measures, and use this framework to evaluate and optimise the use of transport measures and to investigate the effects on equity among population subgroups subdivided by household income in the greater Oslo area. We use the RETRO model (Vold, 1999) to calculate transport quality data and travel demand between zones for car, public transport and slow mode (walk/bicycle). These data are then used in the cost benefit analysis. The cost benefit analysis is summarised in a social efficiency function. The function is the net sum of costs and benefits in an alternative scenario relative to a base scenario. The base scenario describes the situation in the mid-1990s except that charges at the toll ring are set to zero.

For each of 12 alternative scenarios we select a package of available measures and optimise social efficiency, in accordance with the principles underlying marginal cost road pricing. We may subdivide marginal cost road pricing into first-best and second-best road pricing strategies. We have a first-best strategy if link-based road charges on all links are available for optimisation. A second-best strategy uses one or a few available measures for optimisation. The measures that we will consider for second-best road pricing are charges at the toll ring around the Oslo city centre, parking charges, fuel taxes and annualised car taxes. The shadow price of public funds is set to either zero or 0.25[2]. Hence social efficiency may vary because of the measures available for optimisation or because of the value of the shadow price of public funds.

[2] For consistent comparison of results from different case city cities studies in the AFFORD project, all partners in the AFFORD project used these values for the shadow price of public funds.

The first-best road pricing strategies imply separate charges on each road link in the network. Modelling of the *first-best solution* is possible only if a real network representation is applied. Fortunately, the RETRO model includes an EMME/2-database[3] with a real network representation of the road network in greater Oslo.

The second-best pricing strategy that optimises the overall level on the measures is the *second-best solution.* The level of the parking charges is determined as the optimal overall relative change of all parking charges relative to the base scenario. The fuel taxes are similarly determined as the optimal relative change of the fuel tax etc. A general numerical optimisation algorithm is used to maximise the social efficiency function with respect to the relative changes of all the transport measures simultaneously.

To compute equity effects we make use of the disaggregate structure of the model system. We subdivide the population into eight household groups by household income. Each group contains approximately the same number of individuals. The demand model is constructed by using the original data on the travel behaviour of individual agents to construct synthetic zonal populations, conforming as closely as possible to the real spatial distribution of the household income groups. This allows us to compute consumer surpluses for each household income group in each of the zones. Aggregating over zones, the consumer surplus of each household income group is obtained. A Lorenz curve and a corresponding Gini coefficient[4] are used to assess whether the consumer surpluses of the different subgroups improves or worsens equity relative to the base scenario.

Two schemes for redistribution of the revenue from road pricing are applied. The first is redistribution to households in amounts proportional to each household's initial income, i.e. as a constant percentage point tax relief to all income earners. We also use an alternative redistribution scheme in which all individuals receive the same nominal amount of money, large enough (after tax) to exactly deplete the revenue generated by the road pricing policy (flat redistribution). For all scenarios with a shadow price of public fund of 0.25, the proportional redistribution is considered more appropriate, whereas the flat distribution scheme is considered more appropriate for scenarios where the shadow price of public funds is set at zero.

To find marginal cost prices in a real world situation some sort of transport model and an optimisation algorithm is necessary. The methodological questions carry considerable interest in their own right. In this study, we go into much detail on methodology. The purpose of the methodological part of the report is to provide an example of how pricing strategies in general can be analysed. There are of course unresolved questions and shortcomings in our approach, and we want to point them out for future research. By no means do we want to say that one cannot use other kinds of transport models than the one we have used, or more refined calculations of social efficiency, or better optimisation methods. However, by and large our approach has been shown to work and to give plausible results. By reporting it in detail as an example of a workable approach we hope to invite other studies of a similar nature. There is still very much to be learned about marginal cost pricing by

[3] EMME/2 is a computer system for representation of real networks in urban areas. The real network is represented in an EMME/2-database. The system includes assignment algorithms for calculation of transport quality data in the networks (see EMME/2 User's Manual).

[4] See Chapter 6 for a short introduction to the Lorenz curve and the Gini coefficient.

comparing optimal prices in different settings using the same model and methods, and optimal prices in the same setting using different models and methods.

The structure of the report is as follows. In chapter 3 we set out the general conceptual framework for making the move from textbook analysis of marginal cost pricing to analysis of real world applications. Here we build on existing theory presented in Deliverable 1 of the EU project AFFORD (Milne et al., 1999). We add a short general description of cost benefit analysis of transport strategies (i.e., social efficiency measurement in transport). We also stress that fast run times of the transport model is an essential characteristic for the purpose of finding marginal cost prices. Chapters 4-6 sets out the methodological approach that we used in the Oslo case study in AFFORD. In Chapter 4, transport models and their use in calculation of social efficiency are discussed, and the particular transport model and cost-benefit analysis methods used in the present study are presented. Chapter 5 explains the principles that were used for the simultaneous optimisation of transport measures, and chapter 6 explains the principles that were used for the equity analysis.

Chapter 7 contains the case study for Oslo. In this chapter, the framework developed in chapters 4, 5 and 6 is used to determine first-best and second-best marginal cost road pricing, both for a shadow price of public funds of zero and 0.25, and to study the associated equity effects. Chapter 8 contains discussion and conclusions. In section 8.4 we compare our results to previous studies of marginal cost road pricing for Oslo, and also comment on differences in the layout of the studies.

Some of the methodological issues are treated in detail in the appendices. The Simplex algorithm by Nelder and Mead (1965) that is used to obtain second-best solutions is presented in Appendix I, and Appendix II contains supplementary results from the cost-benefit analyses.

3 Making the concept of marginal social cost pricing operational

As urban transport problems grow more severe and tested policies to curb them seem to fail, political support for marginal cost pricing principles is increasing. There is a growing chance that marginal cost pricing policies (road pricing among them) might actually be implemented in European cities in the not too distant future.

It is high time, then, to make the move from textbook analysis of road pricing to the analysis of real world applications. Deliverable 1 of the AFFORD project (Milne et al 1999) was designed to prepare the ground for such a move. The same framework, with slight modifications, is adopted here.

A central point is that to compute the level of the charges in an urban context, some kind of model that may be optimised with regard to social efficiency is needed. A careful analysis is necessary to identify the prices that should and could be set at marginal cost. Ideally, the model to be used should be chosen so that these prices are all available as instruments in the model, which also reflects the corresponding marginal costs in sufficient detail. More often than not, however, the resources for model building are limited, and the limitations of the available model act as constraints on the pricing issues that can be addressed and the level of detail that can be achieved.

3.1 Marginal cost pricing

Economic theory tells us that social efficiency is maximised if (and only if) prices are set equal to marginal social costs. Thus, in the presence of congestion and environmental externalities, every traveller on the urban road network should be made to pay a charge for her use of the road infrastructure, equal to the additional cost that her trip confers on other travellers and non-travellers at this particular location and time. Similarly, every public transport passenger should pay the marginal cost of her trip to the public transport company, plus the marginal cost she confers on fellow passengers by contributing to overcrowding in the public transport vehicles, delaying them at boarding and alighting etc. Public transport operators should likewise pay a charge equal to their marginal external costs.

It is easy to show how the principle of marginal social cost pricing applies in simple textbook settings of one road link with travellers who differ only in their willingness to pay for using the link. Making the concept operational in real world situations is, however, a much more complex task, and requires careful consideration of the *setting* and the *dimensions of choice* open to the travellers. While it is clear that some kind of local transport model is needed to maximise social efficiency and thus find marginal cost prices in real world situations, the characteristics of the available model could confine us to consider only some of the aspects of behaviour and choice open to travellers. Furthermore, even if we could build the model we want, the availability of data and the possibility of measurement will also act as constraints.

According to Milne et al. (1999), ideally one should charge each traveller according to her particular driving style, the characteristics (emissions, road wear) of her vehicle, as well as the more obvious dimensions of the length of the journey, the number of trips and the time and place of driving. Only then will socially optimal decisions be made. Such ideal first-best pricing is generally infeasible, not only because it is costly to implement, but also because it is difficult to make operational: We do not possess the models and the data to find optimal charges.

3.2 Settings and models

Marginal cost pricing in real world applications must be defined relative to a certain *setting*. By this we mean that we must define the system that we are studying, and consequently the system's outside environment. Pricing inside the system is not thought to affect behaviour outside the system. Furthermore, a setting defines the level of detail at which marginal costs are studied and defined, as well as the agents of the system and the dimensions of choice open to them. Both first-best and second-best pricing must be defined relative to such a setting.

Broadly, four different settings may be distinguished: focusing on road transport; covering multimodal transport; covering interactions with inter-urban transport; and covering interactions with land use. The pricing problem in each of these can be studied with the appropriate models: Detailed simulation models or tactical transport models for the road transport oriented setting, strategic models for the multimodal setting, and integrated land use/transport models or perhaps spatial computable general equilibrium models for the broadest settings. No single model can in practice address all relevant issues in all settings. In particular, to address marginal cost pricing of many modes simultaneously, the level of detail of the simulation models will have to be sacrificed, and to address marginal cost pricing in transport and other markets simultaneously, the real network representation of transport supply might have to be sacrificed.

It was the intention of the EU project AFFORD (Milne et al., 1999; Fridstrøm et al., 1999) to compare optimal marginal cost pricing in these different settings, as derived from the different kinds of models. However, very much more remains to be done in this area.

3.3 First and second-best

First-best marginal social cost pricing in a particular setting means that the price of any action open to any agent considered in this setting is equal to its marginal social costs. Thus, we use the concept of first-best pricing even for a pricing scheme where not every conceivable dimension of choice is taken into account. It is sufficient for us that every dimension of choice that is modelled in this setting is taken into account.

In first-best pricing, we should be able to set separate charges on the use of every link in the network, to differentiate between periods according to the level of traffic, and to differentiate between users groups to the extent that their actions impose different marginal external costs. However, these requirements are relative. Our model may not represent all links in the real transport network, time periods may be very coarse, and we may not be able to differentiate between types of private cars or public transport vehicles. Nevertheless, these shortcomings of the model does not preclude us from calling the optimal solution from the model a first-best, as long as it is also judged impractical to implement marginal cost pricing at a finer level of detail. The first-best pricing scheme should represent an ideal situation while not being too unrealistic.

Second-best pricing, then, are the prices that maximise social efficiency subject to constraints on the free use of the charges defined in a particular setting. These constraints may be technological, institutional, legal or political. Second-best solutions are defined relative to the same setting as the first-best, so they involve the same types of costs, the same dimensions of choice, and the same exogenously given environment as the first-best. For some reason, though, the free use of some of the instruments available in the first-best is now barred.

The second-best situation that is of most interest to us is when charging on all of the links is impossible, either because it is technologically infeasible at the moment or because it is very costly.

Milne et al distinguishes between the following types of second best situations:

1. Insufficient power of pricing measures to differentiate
2. Distortions in other routes
3. Distortions in other modes
4. Distortions in other sectors
5. Shadow price of public funds.

When comparing first-best and second-best solutions on partial equilibrium approaches focusing on the transport sector, the fourth and fifth of these types are usually taken as facts of life, prevailing both in the first and second best. Focussing on the transport sector, only 1-3 is what distinguishes second best from first best. A first best solution might therefore be calculated with or without taking the shadow price of public funds into account.

Conceptually, type 1 concerns the difficulty of adjusting prices to marginal cost at every moment in time, as well as at every point in the road network. It also concerns our inability to differentiate between users with different marginal costs. However, when using a transport model to find optimal second best prices, our inability to differentiate may stem not from some technological or information problem in the real world, but from simplifying assumptions of the model. As already pointed out, unless the model we are using is obviously not very well suited to the setting we have defined, we will not count constraints imposed by the model as giving rise to second best solutions. Thus, second best solutions will usually be of type 2 and 3.

3.4 Our setting

We now move on from these general points about how to make the concept of marginal social cost pricing in transport operational, and consider the particular setting (or settings) used in this report.

We consider the following external marginal costs in the urban transport system:

1. Congestion costs
2. Infrastructure damage
3. External accident costs
4. Noise
5. Local emissions
6. Global emissions

These are the costs that need to be addressed by a marginal social cost pricing strategy. This means that for example visual intrusion and barrier effects are not considered.

We then assume these costs to result from the following dimensions of traveller choice (corresponding to the transport model that we have):

1. Car ownership
2. Trip frequency
3. Destination choice
4. Mode choice
5. Route choice

This means of course that we do not consider the dimensions of choice of the public transport operators, or the pricing scheme necessary to induce optimal behaviour on their part. Instead, we assume it possible to regulate their behaviour by other means. (We *do* however consider the marginal external costs of public transport operation, even if we envisage a situation where they need not be internalised by charges).

It also means that we do not consider land use and choices of location, but regard them as given. Neither do we consider the choice of departure time. Finally, we disregard some of the subtler choices that are open to travellers, such as the choice of vehicle size and technology, the choice of driving style, the choice between different parking opportunities at the same destination etc. Next, consider the following prices that might be set at marginal social cost in a first-best solution:

1. Taxes on the purchase and licensing of private cars
2. Fuel taxes
3. Public transport fare
4. Parking charges
5. Link-based charges.

It turns out to be difficult to find a first-best solution taking all these instruments into account. This is because the link-based charges of a first-best solution are very numerous. Given that first-best means being able to levy charges on all links, no method that we are aware of exists to optimise social efficiency using all five types of instruments *simultaneously.*

However, it *is* possible to arrive at optimal or near optimal levels of car taxes and public transport fares, taking the "first-best" charges on the links as given. It should then be possible to iterate between finding link charges and finding car taxes and fares, to arrive at a more comprehensive first-best solution. However, we have not tried to do so, and so we define the first-best solution as involving given levels of car taxes and public transport fares. To find the marginal cost prices in the first-best situation in this report, we only use the link-based charges. The first-best link charges could actually be split in two parts, one representing the minimal external costs of fuel use per litre, and the other representing all other external costs. With ideal link charges, parking charges would have no role to play to internalise external costs incurred while driving, so they should be set to cover marginal costs of parking provision. Thus our method of finding a first-best solution in this report can be interpreted as finding optimal levels of instruments 2, 4 and 5. It consequently defines a first-best solution in terms of given levels of car taxes and public transport fares.

With regard to second-best solutions the picture is different. As the number of links that can be charged in a second-best solution is low, by using quite another method of optimisation than in the first-best case, it is feasible to optimise social efficiency using all five types of instruments. Other instruments, such as public transport subsidies or public transport frequency, might also easily have been included.

The use of these *additional* instruments in second-best solutions make them the second-best solutions of pricing problems whose first-best we have not been able to compute. Thus we are not able to say by how much they fall short of the first-best solution. Nevertheless, they might carry considerable interest in their own right.

In the context of the AFFORD project, second-best solutions whose corresponding first-best has also been found are consistently compared. Second-best scenarios for Oslo in this context includes scenarios with charges levied on the same links as the present toll ring, fuel tax, annualised car taxes (i.e., the vehicle tax) and parking charges. The day is subdivided in peak and off-peak periods and parking charges and tolls could be different in these two periods. In addition we analyse a few medium-term effect scenarios where car ownership can change with respect to the fuel tax and annualised car tax. Corresponding medium-term first-best scenarios were beyond the scope of this report. Hence, in this study there is no comparison between medium-term first-best and second-best scenarios.

3.5 Policy packaging

The economics literature on the application of marginal cost pricing to transport have typically concentrated on rules for setting one single price at marginal cost at a time, or – recognising that prices may not be at marginal costs on another route or another mode – devising second best pricing rules for the case of a single mispriced route or mode. This works out well as long as the levels of these few marginal costs are unaffected by the incentives given to travellers with regard to other dimensions of choice. However, in a real transport system, the level of the marginal external costs at one point in the system is related to the levels at other points in very complex ways. To find optimal prices (which will be marginal cost prices) one will then have to apply a social efficiency function that is based on a transport model and perform repeated runs of the model until the function is optimised.

In second-best cases, the available policy instruments will typically have to take care of many tasks, and there is certainly no easy one-to-one correspondence between instruments and marginal costs in different parts of the system.

Thus in all real world applications, we must necessarily consider a whole range of pricing instruments simultaneously. In second-best cases, the range of pricing instruments that we apply should cover among them, if at all possible, all the relevant dimensions of choice open to the agents in the system.

An important feature of the policy packages that we consider is that they are specifically *marginal cost based*, so that first-best and second-best pricing rules are at their core. This does not however preclude the inclusion of non-price instruments in the package. Such other instrument must preferably be continuous to facilitate optimisation. In a broad setting, overall public transport frequency might be such an instrument.

In our notation, a policy package and a strategy is the same thing. Thus, we will often speak of a pricing strategy when the policy package consists of price variables only.

There is still a lot of work to do in order to compare first and second-best prices derived from different models and for different settings. There are also much more to be learned from comparing the second-best solutions of different (imperfect) policy packages on the same model and in the same setting.

3.6 Benchmarks

The natural benchmark for any second-best package is of course the first-best solution. The base case where all instruments are at their current levels is however a useful opposite extreme. The level of the social efficiency function for the base case is 0. The efficiency of all second-best solutions can then be expressed as a percentage of the level achieved in the first-best (assuming the instruments that are unavailable in the second-best are fixed at their base case level).

3.7 Social efficiency

A welfare function in economics is some function of the utility levels of all members of society. The welfare function is increasing in all of these individual utilities. For our purposes, we also require that it should be linear in the individual utilities, and than every individual utility carries the same weight. This means that issues of distribution and equity can be totally separated from the efficiency issues.

If such a welfare function has been specified, the social efficiency of an allocation or a state of the society can be defined as the level of the welfare function in that state. The term 'economic efficiency' is often used instead of social efficiency. We prefer 'social efficiency' here, to make it clear that environmental and other non-monetary costs are certainly to be included when the social efficiency of a state is calculated.

We often assume in transport economics that the individuals have constant marginal utility of time savings and constant marginal utility of income. This is either stated explicitly or implied by the models used. The result is that demand can be expressed in terms of generalised cost and does not depend on income. Consequently, aggregate demand can be interpreted to be the demand of a utility maximising representative consumer with a quasi-linear utility function. The standard logit and nested logit models of transport demand imply these assumptions.

We are no better than the rest, so we adopt these assumptions. The standard methods of performing cost benefit analysis in the transport sector, which we adopt, follow from this. Starting from a base case situation where the level of the welfare function

W (the social efficiency function) is 0, the social efficiency of a new state in the transport system can be written as the sum of four elements:

1. User benefits in the transport system. Thanks to the strong assumptions, implicit in the transport model, that allow us to see aggregate demand for transport as the demand of a representative consumer, user benefits can be measured by the logsum formula, or equivalently as Hotelling's generalised consumer surplus.[5]
2. Producer surpluses of public transport operators, toll system operators and parking lot operators.
3. The financial surplus of the government, including tax revenue from transport taxes and charges.
4. External cost savings.

All four elements are measured relative to the base case, so they involve changes in benefits and costs from the base case.

The three last terms can be added to the first because the representative consumer has an indirect utility function of the "quasi-linear" form $v(\mathbf{G}) + m$ – where **G** is a vector of generalised costs in all transport markets, $v(\mathbf{G})$ are the user benefits in transport as measured for example by the logsum formula, and m is income – so user benefits are measured in monetary units. Monetary changes for operators, government and third parties may be interpreted as changes in the income of the representative consumer.

In the calculation of user benefits (item 1 above), perceived costs must be used. Obviously they will include taxes and charges that are mere transfers between travellers and the government, or between travellers and the operators. How do we make sure that resources used or saved in the evaluated strategy are valued at their true social cost? It turns out that correct assessment of the change in tax revenue leads to the result that resources used or saved are valued at their social cost. For resources that can be obtained by producing or importing more, like the costs of operating a car, the true social cost is net of taxes. This is the cost we get if we enter the gross costs including taxes in the calculation of net user benefits, but add the tax revenue that the government gets from the increase in car use as a benefit under item 3 above. Conversely, if resources cannot be newly produced or imported but are drawn from other consumption and productive use, their true social value is their price including taxes. In that case, which typically applies for the use of labour, the government gets no new tax revenue, so (labour) taxes should not be added as a benefit under item 3.

The same principle applies to transfers between travellers and the operators in the form of fares and other charges. Obviously, as a part of perceived costs they are deducted under item 1, user benefits, to arrive at the net benefits. But because they are not true social costs, they must also appear under item 2 as revenue for the operators. This is why item 2 takes the form of producer surpluses - that is, revenue minus costs. So the two first items are really consumer surplus plus producer surplus, while items 3 and 4 are corrections to arrive at true social costs of resources used in the strategy.

[5] See Oppenheim (1995) for a very consistent application of the representative consumer approach to all standard disaggregate transport models.

The assumptions necessary to convert environmental damage to a monetary cost are strong. Only for some of the environmental costs - typically air pollution, noise and accidents - do we venture to enter monetary values.

These four items added together make up the social efficiency function W. Of course, all four items are flow variables, and so they must be calculated for a certain period of time. For pricing strategies, where the policy variables are prices and charges that may be reset almost continuously, a period of one year is the most convenient. For cost benefit analyses of infrastructure measures, a considerably longer period of 25, 30 or 40 years is commonly used. This of course involves the need to use a discount rate.

To analyse the social efficiency of a pricing strategy, the output from the transport model (plus some appended model of environmental effects) is used to calculate the social efficiency function. To analyse first or second-best marginal cost pricing in a real world situation, the maximum attainable level of the social efficiency function must be found. Inevitably, this means some systematic form of repeated runs of the transport model, each time calculating the social efficiency function, until we are satisfied that no improvement is possible. The level of the prices and charges at this optimum must be the marginal cost prices, first or second-best as the situation may be.

3.8 Discussion

This chapter has emphasised that in a real world application of marginal cost pricing, more often than not we cannot find the marginal cost prices by analysing traffic on single links separately, or by the use of very simple analytical models. This is because link flows and therefore the marginal social cost on each link is a function of the prices set on all links, as well as some system wide prices, like the vehicle tax. So inevitably, we are compelled to use a transport model to compute the whole set of marginal cost prices simultaneously. A social efficiency function is maximised by performing repeated runs of the transport model. The ensuing optimal prices are first-best marginal cost prices if optimisation was carried out without constraints and with respect to a set of prices that has a one-to-one relationship with the set of costs considered in a particular setting. Otherwise they are second-best. Comparisons of first and second-best solutions should always be carried out within the same setting.

Social efficiency, as calculated here, is a function of the pricing variables. The pricing variables determine the transport model output (origin-destination and cost matrices, as well as the level of external effects). These outputs are used as input to the cost benefit calculation. The whole composite function can be computed at every point, but the derivatives cannot be computed. It is this fact that makes it necessary to use an optimisation technique that does not use derivatives.

The need for repeated runs compels us to use a transport model with relatively short run times. This means either a model with relatively little detail, or with very efficient solution algorithms. Thus the details of model building need to be considered right at the outset of an analysis that aims at finding the best ways of implementing marginal cost pricing in practice. If one feels that the important thing is to introduce marginal cost pricing simultaneously on many modes (a broad setting), and to differentiate between many user classes, one may have to settle for less details regarding times of day or network representation - or devote more effort to efficient programming.

Often, there is only one model available and no funding for new model building. This is why virtually nothing has been done to compare optimal marginal cost pricing in different settings, as derived from different kinds of models. To get a clearer understanding of marginal cost pricing in practice, one would also like to see much more in the way of comparing second-best solutions of different (imperfect) policy packages on the same model and in the same setting.

Some decision-makers remain sceptical about the use of transport models. Others deplore their inability to represent accurately the link flows on every link, and want models with ever more detail in every respect. While it is indeed essential for analyses of marginal cost pricing to get the link flows (and the link volume delay functions) right, one will also have to be concerned about run times if the model should be used for analyses of pricing policies. If no model is used but simple rules of thumb, there is no way of judging what is achieved and what is lost.

Equity issues are important for practical implementation of marginal cost pricing. A feature of the assumptions underlying present day transport models is that demand can be interpreted as the demand of a representative consumer. This allows for a complete separation of efficiency and equity issues, and opens the way for a separate equity analysis of the pricing strategies. This possibility is also crucially dependent on the use of a disaggregate transport model.

4 Evaluation of pricing strategies in greater Oslo

In the present report, we use cost-benefit analysis to calculate the effect of road pricing strategies on social efficiency. All significant effects and interactions must be taken into account in order to get a good account of the individual and total effects on social efficiency. It must be specified whether effects are considered short, medium or long term.

Usually it is not possible to obtain empirical observations of the effects. To perform cost-benefit analysis then, it is necessary to apply a transport model, where the interactions are represented.

Simple models are easy to understand and to use. The drawback is however that the output is sparse and they represent the interactions only to a very limited extent. Consequently, a cost-benefit analysis that is based on output from a simple transport model will contain only coarse information.

For the purpose of cost-benefit analysis, a real network model representing several modes and elastic demand is often more appropriate. A model of this type produces detailed results, which again allows for a more detailed cost-benefit analysis.

Minken (1997) describe a framework for cost-benefit analysis of the use of different transport measures in transport systems. We have coupled this framework with the regional-real-network transport model for the greater Oslo area RETRO (Vold, 1999) and a national model for car ownership (Ramjerdi and Rand, 1992).

This chapter and the two following chapters take a closer view at the main methods used to find first and second-best marginal cost prices and evaluate their social efficiency and equity effects in the present study and in Fridstrøm et al (1999;2000). The transport model is treated in section 4.1, and social efficiency calculations are treated in section 4.2. Optimisation is treated in chapter 5 and equity measurement in chapter 6.

4.1 Requirements on the transport model

Transport models can be used to increase the understanding of interactions in the transport system and to quantify changes caused by transport measures. Simple analytical models can be sufficient for some purposes, but more complicated real network models are often needed. In models of passenger transport, transport modes are often classified as car, public transport or slow mode (walk/bicycle). Often these general classes are refined. For instance, the car mode can be subdivided in small and big cars and in car driver and passenger. Public transport can be subdivided in bus, tramway, subway, train, boat etc.

First-best road pricing operates at the level of road links in the network by levying individual charges on each link in the network. Accurate modelling of the first-best solution is thus possible only if a real network representation is applied.

In real network models, algorithms for route assignment and transit assignment can be used to calculate the transportation level of service for the modes (see Sheffi, 1985, for an introduction to assignment algorithms). Different ways of doing this includes route assignment with algorithms for fixed or variable demand (Vold, 1999; Sheffi, 1985).

A fixed demand algorithm performs route assignment for a fixed origin-destination (OD) matrix containing the number of trips between geographic zones. Introducing variable demand refines the approach. The demand model calculates the number of trips as a function of the transport level of service. The complexity of demand models depends on the number of choice dimensions (i.e., route choice, mode choice, and destination choice and trip frequency) and whether or not travellers' choices are modelled in an aggregate or disaggregate (behavioural) way.

Available data (i.e., travel surveys and demographic data) can be used to construct a prototypical sample. The prototypical sample constitutes a disaggregate synthetic representation of the population. A representation of the population with at least two representative users is needed in order to do some kind of equity analysis to quantify the effects of how changed prices and external costs affect equity among different population subgroups. A consistent model including disaggregated representation of the travellers, trip frequency, destination choice, mode choice and route choice (assignment) for peak and off-peak periods can be obtained by application of nested logit models (Ben-Akiva and Lerman, 1985). Input to nested logit models includes transport quality data for the different modes, demographic data characterising the attractions in the zones and economic characteristics of the traveller.

The demand and assignment parts of transport model systems can be loosely or closely integrated. A close integration may be more effective with respect to the computation time required, whereas a loose integration may be more flexible with respect to model modifications and refinements.

There is an important distinction between short-term, medium-term and long-term effects of road pricing measures. In the medium run, travellers are better able to adjust and adapt to price signals than in the short run. Hence, medium-run demand tends to be more elastic than short run demand (Oum, Waters & Young, 1992).

A traditional 4-stage real network transport model with route choice, mode choice, destination choice and trip frequency can basically be considered as a model for calculation of short-term effects. That is, the model calculates the travel behaviour after new levels on road pricing measures are known in the population (the day-to-day travel decisions) but before people and firms have adjusted with respect to their car ownership and location choice. We consider car ownership as adjustable in the medium-term, and that location choice is a long-run effect.

Hence, a four-stage real network transport model or a combined model of trip frequency, destination, mode choice and route choice, extended with a car ownership model, should be capable of taking into account how people are able to adjust their car ownership in the medium-term time horizon.

Further refinements of transport models include intermodality and integration of freight and passenger transport (Oppenheim 1995 ch. 8) etc.

4.1.1 The RETRO model

The transport model for the greater Oslo area (RETRO) is a four-stage real network model (Vold 1999). The RETRO model that was used in this study includes an EMME/2-database with a real network representation of the road network. RETRO can be connected with a car ownership model that was originally developed as part of the national model system for private travel (Ramjerdi and Rand 1992; Rand and Rekdal 1996). The car ownership model is based on theory from de Jong (1989). It can be used to predict the total number of cars for population subgroups in the Norwegian municipalities with respect to income and fixed and variable car costs and, hence, the relative change in car availability as compared to a base scenario. The relative change in car availability is used as input to the travel demand model. Car ownership is fixed, however, if the car ownership model is made inactive.

The car ownership model is not responsive to congestion on the road network, nor to the availability of parking or the public transport service level and public transport prices. Of the prices that we considered in our settings (see section 3.4), only car taxes and the fuel tax matters for car ownership in our model. As our first-best calculations only involve link-based pricing instruments; car ownership is unaffected in the first-best solution - which of course makes it the short-term first-best solution. To be able to compute medium-term first-best solutions, obviously one needs a car ownership model that responds to congestion levels, the availability of parking and the public transport supply. We are not aware of any work that has solved this problem.

For travel demand, RETRO includes a disaggregate nested logit model that calculate mode choice and destination choice, whereas a geometric distribution is used to calculate trip frequency. Consistency between these parts of the model is secured by including the logsum from the nested logit model in the trip frequency model. The model was estimated with data from a travel survey from 1989-1991 (Hjorthol and Larsen 1991), where a sample of people were asked to fill out a questionnaire about their travel behaviour before and after the implementation of the toll ring. The data were used in estimation of the trip frequency and nested logit models, which together constitutes a random utility model for travel demand and is the demand part of the transport model system.

The prototypical sample that represents the model is used as input to the travel demand model together with transport quality data. Some of the transport quality data are obtained from empirical sources whereas others are calculated by EMME/2 with a real network representation of the roads and public transport network representation that corresponds to the situation in mid 1990s (Holsæter 1999). The travel demand model and EMME/2 are run interchangeably until convergence of travel demand and travel supply is achieved (Figure 4.1), where transit assignment can be based on demand dependent or demand independent transportation level of service (see Vold 1999).

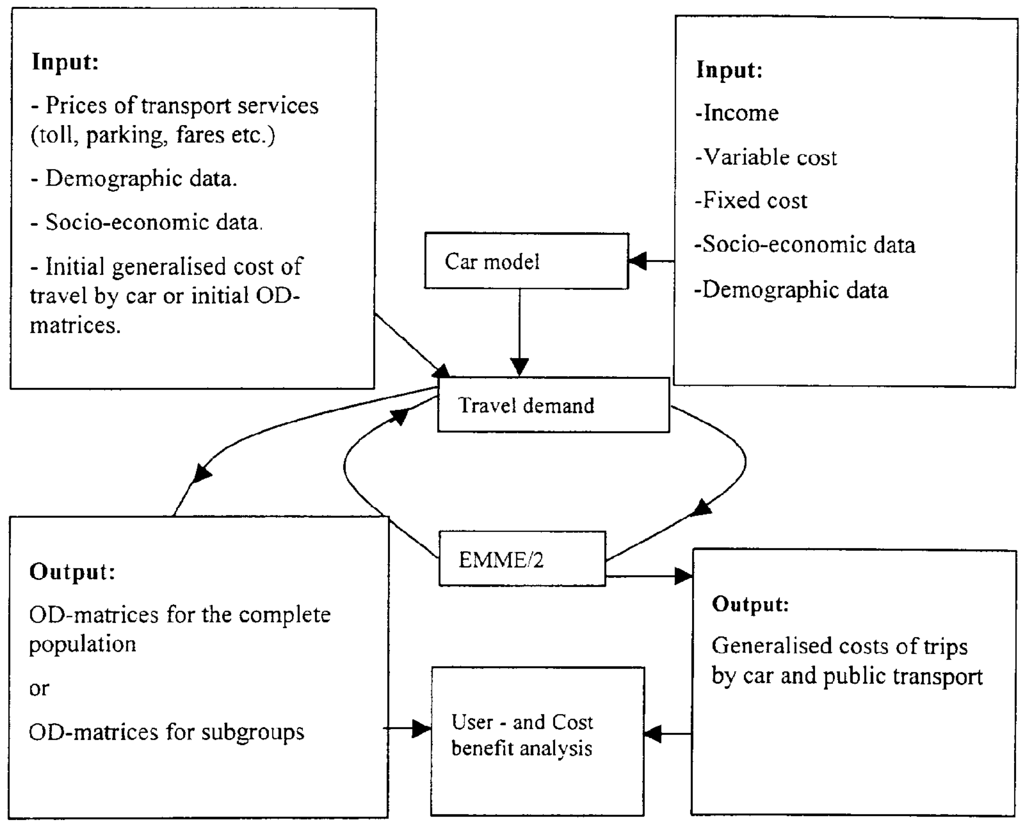

Figure 4.1. Flow chart of the model system. Note that the travel demand model and EMME/2 are run in an iterative loop. Iterations are performed until the generalised cost of trips by car (as calculated by EMME/2) and the demand of trips by car (as calculated by the travel demand model) is in equilibrium, until divergence occurs or until a maximum number of iterations.

The demand part of the model system has 49 zones, while the EMME/2 network part has 438 zones. Thus, at the point of interaction between these two parts, demand in each of the zones must be distributed to a finer system of zones. Obviously, these two parts are loosely integrated.

Our model does not distinguish between travel time periods in a very detailed way. Only "peak" and "off-peak" periods are considered. Moreover, in the model there is no substitution between the two periods. Thus the model fails to pick up any efficiency gain originating from travellers choosing a less congested time of travel – it captures only behavioural changes related to mode choice, destination choice, or trip frequency. A finer representation of travel time periods, with endogenous choice between them, would have moved travellers from one period to the other.

The whole model system is implemented on a UNIX platform. The latest version of the car ownership model (Phase IV) was converted from the computer language Pascal to C before it was implemented as part of RETRO. The low number of zones in the demand part of the model system and the low number of time periods helps reduce run times, while the loose integration of the demand and supply part increases run times. A full transport model run, including iterations to user equilibrium in the assignment part and equilibrium between supply and demand, takes about 2 hours. This means that an optimisation to find second-best solutions to the marginal cost pricing problem takes 2 days or more. Obviously, one would not want to make this system much more complex if it is still to be used for analysis of pricing strategies.

An important facility of the RETRO model is the policy variables that automate the optimisation process. The policy variables are parameters that are used to change the levels on the overall frequency of public transport and certain prices and taxes that are used in the model.

Table 4.1. Policy variables

Variable	Description
x_1	The overall fuel tax rate level. Multiplied by the fraction of distance based charges that are due to fuel cost.
x_2	Non-fuel distance dependent car tax rate level.
x_{3k}	The overall level of toll charges at time, *k*, of the day. Multiplied by the reference tax (8.1 kr) that is paid to enter inside the toll cordon.
x_{4k}	The overall level of parking charges at time, *k*, of the day. Multiplied by the reference parking charges in zones.
x_5	The overall level of public transport fares.
x_6	Multiplied by the fraction of fixed car costs that is due to the annual fee and a fraction of the depreciation. The fraction of the depreciation is equal to the percentage of tax paid when buying a car.
x_{7k}	The overall frequency of public transport in time period *k*

The policy variables are usually set at 0 or 1 in a base scenario. Alternative scenarios can be run where the policy variables are changed by certain amounts. The policy variables are multiplied by corresponding quantities in the model. The present version of RETRO (v.1.0) includes seven policy variables (Table 3.1).

In the present study, the policy variable of *public transport (PT) frequency*, x_{7k}, was *not* used as an exogenous input to the model. PT frequency was made to respond to changes in public transport demand, although not in a proportional way. Thus, decision-makers were assumed to adjust PT frequency to avoid overcrowding while securing a minimum level of frequency. Essentially, frequency adjusts between limits given by the current level-of-service ±40 per cent.

RETRO is based on the assumption that car drivers are charged both on entering and leaving the area enclosed by the toll ring. In reality, however, car drivers are charged only when the entering the area. Fortunately almost all trips are round trips. Hence, the inconsistency is minor. RETRO calculates the actual toll charge by multiplying the policy variable for toll charge x_{3k} by 8.1, i.e. $x_{3k} \cdot 8.1$. The average one-way charge per car passing the toll ring in 1995 was NOK 8.4, which corresponds to a value of x_{3k} equal to 0.52.

4.2 The social efficiency function

A pricing strategy is a package of policy variables at our disposal and the overall levels of these measures. We consider optimisation of pricing strategies consisting of the fuel tax rate, taxes on car ownership, plus parking charges and toll charges at the present toll ring in periods of peak and off-peak traffic load. This gives six available instruments. When policy variables are set to 1, they equal mid 1990s levels of the corresponding instruments.

In section 3.7, we saw how the social efficiency of a strategy consisted of four elements; user benefits, producer surpluses, changes in government revenue and changes in external environmental and accident costs. All elements are differences from a base scenario, so that the social efficiency of the base case is 0. Introducing some notation, we denote the social efficiency function W, the sum of the three first mentioned elements is denoted EEF[6] and the fourth element, the system external costs, EC. We have:

$$W = EEF - EC$$

where all components represent the absolute changes relative to a base scenario. By definition the value of W for the base scenario itself is zero. Policy variables in the base scenario are set to one for all variables except toll charges, which are set to zero.

The function *EEF* is the net present value of economic efficiency and *EC* is net present value of external costs of accidents, noise and pollution. The formula for the net economic efficiency can be expressed as

$$EEF = B - I + \lambda \cdot PVF,$$

where I is the present value of the cost of infrastructure investments, compared to the base scenario. The net present value of finance of a policy *PVF* over a 30 years period is defined as the discounted net financial benefit of the policy to government and other providers of transport facilities, both public and private:

$$PVF = -I + \sum_{i=1}^{30} \frac{1}{(r+1)^i} \cdot f,$$

where f is the net financial benefit to transport suppliers and government in the modelled target year as compared with the base scenario and r is the discount rate. We use a discount rate of r = 7%.

The shadow price of public funds λ is applied to changes in the government and local authority budget balances, assuming they will have to pay any transport company deficits. The shadow price of public funds reflects the efficiency loss (distortionary effect) involved in raising extra taxes with the already existing tax instruments. However, when considering pricing strategies, we do in fact consider a change in the tax system itself. Almost always these strategies will results in a surplus for the government and local authorities, even after investments and transport company deficits have been covered. To still use the same shadow price of public funds in these cases, we will have to assume that the transport taxes are *not* distortionary. We make this bold assumption, but on the other hand, we evaluate our strategies for two different values of λ, 0.25 and 0.00.

[6] EEF stands for "Economic efficiency function". As we have already agreed that economic efficiency and social efficiency is the same thing, this may be a little inconsistent, but it stems from the notation used in the EU projects OPTIMA, FATIMA and AFFORD projects. In these projects, social efficiency W was also called EEFP.

The present value of the benefits of all years (excluding investments) is

$$(4.1) \quad B = \sum_{t=1}^{30} \frac{1}{(1+r)^t} \cdot (f + u)$$

where u is the net benefit to transport users in the target year as compared with the base scenario. To use the framework outlined above we must, among other things, decide on:

- The target year (comparison year).
- The supposed first year of operation of the strategy.
- What values of time to use for evaluation of the travel time savings and external environmental costs.

The target year and the first year of operation is set at 1995. Separate values of time were calculated for car and public transport in peak and off-peak time periods (see section below 4.2.3), and the external kilometre dependent costs were calculated for car, bus, tram, subway and train (see section 4.2).

The present version of the framework is generally based on prices, taxes and costs as of 1995. The rest of this chapter deals with λ and the decomposition of f and u, and EC.

4.2.1 The shadow price of public funds

There is a close relationship between social efficiency, the scheme for redistribution of revenue from road pricing and the shadow price of public funds. A government appointed committee in Norway has proposed that the official shadow price of public funds in Norway should be set to 0.2 (NOU 1997: 27). This has now been approved.

The value of the shadow price of public funds λ is still a very debatable theme, however. A shadow price of public funds greater than zero can be defended based on arguments that public funds used in transport creates a need for distortionary taxation, while conversely money raised by transport taxes could be used to reduce other taxes, e.g., redistribution of the government revenue from marginal cost road pricing by reducing the tax on labour. In both cases, the economy would function better as prices got closer to marginal costs. This positive effect on the economy is sometimes termed the "double dividend", which in the case of road pricing means that benefits are gained both in terms of reduced external costs (i.e., time benefits, reduced pollution etc.) and improved efficiency in the economy as a whole.

The values of the shadow price necessarily become somewhat subjective. In order to highlight the effects of the value of the shadow price of public funds on social efficiency, we run scenarios that are similar except that the shadow price is zero in one scenario and 0.25[7] in the other.

Zero shadow prices of public funds are based on the assumption that the revenue from road pricing is redistributed such that taxes are reduced by equal absolute

[7] For consistent comparison of results from different case city cities studies in the AFFORD project, all partners in the AFFORD project used these values for the shadow price of public funds.

amounts for all household consumption units. This has no effect on the marginal tax rate on labour and creates no efficiency gain in the economy. A proportional redistribution scheme is assumed in scenarios where the shadow price of public funds is 0.25. For proportional redistribution, the revenue is redistributed back to the households as the same tax percentage relief on household income for all subgroups.

The effect of shadow prices of public funds, and, hence, the effects of the redistribution schemes on equity are presented in section 7.4.

4.2.2 Net user benefits

Assuming separability, the non-discounted net benefit of travellers in the target year, u, can be subdivided in the net benefits of regional trips u_r, the net benefits of long distance trips u_l, and the annual fixed cost K of owning the car fleet.

$$(4.2) \quad u = u_r + u_l - K$$

Only u_r and K can be assessed from the transport model data. However, u_l will also be affected by changes in car ownership. This problem is discussed in section 4.2.4 and 4.2.5 below.

4.2.3 Net benefits of regional trips

The net benefits of regional trips u_r decomposes in benefits for car drivers, for public transport travellers and for travellers by slow mode, m = car, public transport and walk/bicycle, respectively:

$$u_r = \sum_m UB_{r,m} \, .$$

In the sequel, we shall stick to the notation and terminology in Vold (1999). We use "The rule-of-half". Thus, the formula for the user benefits in the transport system under consideration is

$$(4.3) \quad UB_{r,m} = \frac{1}{2}\sum_{i,j,k}(T^0_{ijkm} + T^n_{ijkm})(G^0_{ijkm} - G^n_{ijkm}) \, ,$$

where the number of trips from i to j by mode m in period k ,T_{ijkm} , and the corresponding generalised costs of travel is G_{ijkm}. Superscripts 0 and n refers to the original or base scenario and the scenario when a strategy has been implemented.

We need separate formulas for user benefits due to monetary savings and timesaving. Decomposition of $UB_{r,m}$ relies on the fact that the generalised cost takes the form of a linear combination of monetary and non-monetary items – in essence like this:

$$G_{ijkm} = C_{ijkm} + E_{ijkm} \, .$$

where the monetary cost C_{ijmk} and the non-monetary costs E_{ijmk} are calculated with the aid of the transport model.

The rule-of-half can be written

$$UB_{r,m} = \frac{1}{2}\sum_{i,j,k}(G^0_{ijkm} - G^n_{ijkm})(T^0_{ijkm} + T^n_{ijkm}) =$$

$$\frac{1}{2}\sum_{i,j,k}[C^0_{ijkm} - C^n_{ijkm} + E^0_{ijkm} - E^n_{ijkm}](T^0_{ijkm} + T^n_{ijkm}) =$$

$$\frac{1}{2}\sum_{i,j,k}(C^0_{ijkm} - C^n_{ijkm})(T^0_{ijkm} + T^n_{ijkm}) + \frac{1}{2}\sum_{i,j,k}(E^0_{ijkm} - E^n_{ijkm})(T^0_{ijkm} + T^n_{ijkm})$$

i.e. as a separable sum of monetary and non-monetary elements. Incidentally, this is one of the great advantages of the rule-of-half.

Now, we have that decomposition with respect to monetary and non-monetary costs and periods of peak and off-peak traffic load gives

$$UB_{r,m} = UBC^{peak}_{r,m} + UBC^{offp}_{r,m} + UBE^{peak}_{r,m} + UBE^{offp}_{r,m}$$

where

$$UBC^{peak}_{r,m} = \frac{1}{2}\sum_{i,j}(T^{0,peak}_{ijm} + T^{n,peak}_{ijm})(C^{0,peak}_{ijm} - C^{n,peak}_{ijm}),$$

$$UBC^{offp}_{r,m} = \frac{1}{2}\sum_{i,j}(T^{0,offp}_{ijm} + T^{n,offp}_{ijm})(C^{0,offp}_{ijm} - C^{n,offp}_{ijm}),$$

$$UBE^{peak}_{r,m} = \frac{1}{2}\sum_{i,j}(T^{0,peak}_{ijkm} + T^{n,peak}_{ijkm})(E^{0,peak}_{ijkm} - E^{n,peak}_{ijkm})$$

and

$$UBE^{offp}_{r,m} = \frac{1}{2}\sum_{i,j,k}(T^{0,offp}_{ijkm} + T^{n,offp}_{ijkm})(E^{0,offp}_{ijkm} - E^{n,offp}_{ijkm}).$$

The monetary cost of travel from node i to node j by mode m in period k is given by

$$C_{ijmk} = [(1 + x_1\varphi_m)\rho_m + (1 + x_2\chi_m)\sigma_m]D_{ijmk} + x_{3k}\mu_{ijmk} + x_{4k}\pi_{jmk}$$

where ρ_m is the pre-tax fuel cost per vehicle kilometre of mode m, φ_m is the tax rate on fuel for mode m, σ_m is the pre-tax non-fuel cost per vehicle kilometre of mode m, χ_m is the tax rate on distance dependent car costs other than fuel, μ_{ijmk} denotes the one way toll charge on trips from i to j on routes where it is necessary to cross the toll ring (i.e. car drivers are charged both when they enters and when they leave the area enclosed by the toll ring). The parking fee at destination j at time of day k for mode m = 1 (i.e. car) π_{jmk} was set individually for the destination zones. We have that x_1 is the relative change in fuel tax rate level, x_2 is the relative change in non-fuel distance dependent car tax rate level, x_{3k} is the relative change in toll charge and x_{4k} is the relative change in parking fees at time, k, of the day. The policy variable x_2 is 1 in all scenarios considered in this report, whereas x_1, x_{3k}, x_{4k} can vary relative to the base case. For the other parameters, we use the values given in Vold (1999). The variable D_{ijmk} denotes the distance (km) from i to j at time k of the day for car and public transport, and the logarithm of the distance for slow mode. The assignment algorithm that is used with RETRO calculates it.

The non-monetary cost is given by

$$E_{ijmk} = (H_{ijmk} + \upsilon_{mk} A_{ijmk} + \varpi_{mk} (1 / x_{7k}) W_{ijmk} + \vartheta_{mk} B_{ijmk}) \tau_{mk},$$

where H_{ijm} is the in vehicle travel time (min) $_k$, A_{ijm} is the access (walking) time (min), W_{ijm} the waiting time, and B_{ijmk} the number of boardings minus 1 (i.e. the necessary number of vehicle changes on a trip), and τ_{mk} is the conversion factors between time and money – the "value of time" for modes m = car, public transport and walk/bicycle, and time periods k = peak and off-peak. The values of time for walk/bicycle were set at zero.

In the submodel for travel demand that is part of RETRO, the time values, τ_m, and the corresponding constants for public transport, υ, ω and ϑ, are estimated simultaneously with many other parameters (see Vold, 1999), *and are different from those we use in the calculation of user benefits.*

In order to determine the values of time for calculation of user benefit we have assumed that 44% percent of the peak trips by public transport are work trips, 56% are other trips and 0% are business trips. To determine the value of time for trips by public transport in off-peak periods, we assumed that 26% of the trips are work trips, 74% of the trips are other trips and 0% are business trips. Official values of time per person on work trips and other trips by public transport in 1995 were 46.63 and 33.83 NOK/hour, respectively (SV, 1995). From 1995 to 1997 the salary of labour workers increased by a factor of 1.08 (Statistics Norway, 1997). Based on this, we use average values of time for trips by public transport in peak and off-peak periods of 41.1 and 38.15 (NOK/hour), respectively.

We assumed that 24.1 and 27.7 percent of the trips by car are business trips, respectively, in peak and off-peak, and that the rest of the trips are subdivided to work trips and other trips according to the same subdivision as for trips by public transport. Official time values for work trips, other trips and business trips by car were 46.5, 31.38 and 152.46 in 1995 (SV, 1995). This gives average values of time for trips by car in peak and off-peak periods in 1997 of 68.69 and 73.16 (NOK/hour), respectively, in periods of peak and off-peak traffic load.

This corresponds to the time values, τ_{mk}, for calculation of $UB_{r,m}$ of 1.22, 0.64 and 0.0 (NOK/min) in periods of off-peak traffic load for car, public transport and slow mode, respectively, and 1.145, 0.685 and 0.0 (NOK/min) in periods of peak traffic load, respectively. The value of the constant, υ, for proportional increase in the time value, τ_m, that is used for access (walking) to and from the mode, is set at 2. We set the proportional increase in the time value that is used for waiting time, ω, at 2. Also, the conversion factor for translating vehicle changes into time cost ϑ (min/boarding) is set at 2. This is equal to the corresponding input parameter in the transit assignment algorithm of EMME/2 (Vold, 1999) that is used with the RETRO model.

4.2.4 Net benefits of long distance trips

The net benefits of long distance trips u_l decomposes in benefits for car drivers, for public transport travellers and for travellers by slow mode, m = 1, 2 and 3, respectively.

$$(4.4)\quad u_l = \sum_m UB_{l,m}$$

Since all long distance trips are outside our modelled area, these benefits cannot be measured, at least not in an accurate way. When car ownership is allowed to change, this shortcoming is serious. It is exactly to be able to make holiday trips and weekend trips by car that many people own cars. Public transport is no option for most of these trips.

4.2.5 The cost of owning a car and the benefit of having one

The net cost of owing a car depends on changes in the part of the time dependent depreciation cost that is due to purchase tax and the annual road tax for cars.

It is assumed that the mean annual depreciation cost is 22 000 (NOK/year). According to Ramjerdi & Rand (1992) 83% of depreciation is time dependent (18 260 NOK/year). Of the total time dependent depreciation cost, we let 50% be pre-tax cost, η (NOK/day), and we let 50% be due to tax, $\xi_1 \cdot \eta$ (NOK/day), which implies that $\xi_1 = 1$. The time dependent depreciation cost per day is thus $(1+\xi_1)\cdot\eta = 18260/365 = 50$ (NOK/day).

Let the annual road tax be 1705 (kr/year [1997]). The road tax per day is then $\xi_2 \cdot \eta = 1705/365 = 4.67$ (NOK/day).

Now, let N_c^0 and N_c^n be the number of cars owned by citizen in the region in the base scenario and in the alternative scenario, respectively. According to Røssevold (1997), the total number of cars in Oslo and Akershus, N^0_c, was 355 895, whereas according to the model by Ramjerdi and Rand (1992) the number of cars in 1995 was 390 522. We used the latter figure, which implies that the total revenue from time dependent car taxes is $J^0 = N_c^0 \cdot (\xi_1 + \xi_2)\cdot\eta = N_c^0 \cdot \xi \cdot \eta =$ 390 895 (25 + 4.67) = 10 526 802 (kr/day). The total expenditure on cars is obviously $K = N_c^0(1+\xi)\eta$ = 21 370 230.

The change in the monetary expenses for car owners from the base case to a strategy that changes car ownership is $(N_c^0 - N_c^n)\eta + \Delta J$, where

$$(4.5)\quad \Delta J = N_c^0 \xi\eta x_6^0 - N_c^n \xi\eta x_6^n$$

is the car tax change, and x_6^0 and x_6^n are policy variables for the time dependent car taxes of the base scenario and the alternative scenario, respectively. The policy variable x_6^0 for the base scenario is 1. For the rest of this section, we omit the subscripts on the policy variable x_6 and the number of vehicles N_c.

*

Since, according to our car ownership model, car ownership is not responsive to any of our policy instruments except the fuel tax and the car tax, user benefits can obviously not be calculated at the level of the car ownership model. On the other hand, since the benefits of long distance trips cannot be assessed, a complete benefit calculation at the level of the transport markets is equally impossible. Furthermore, there is a need to account for the changes in consumers' expenses on cars in the scenarios where car ownership is allowed to adjust (that is, in the scenarios where the fuel or car tax changes, and medium term effects are thought to be important). These problems have not been solved in a consistent matter in this study. It does, however, only affect some of the scenarios.

For a first approximation to a solution, assume that car ownership does not produce benefits per se – so the gross benefit of owning a car equals the net benefits of car trips. This is implied by formula (4.2). It seems reasonable to assume that for an individual with a car available, benefits from trips can be separated into benefits from regional trips (inside our study area) and benefits from long distance trips. The net benefits of an individual with a car available will consequently consist of net benefits of both regional and long distance trips by all modes, less the fixed car costs. All of this is implied by the formulas in section 4.2.3 and 4.2.4. However, the long distance trips by car and other modes fall outside our study area.

Since the benefit of long distance trips must perforce be set to zero, some adjustment of the fixed car costs seems to be called for. From the 1997/98 national travel survey (Stangeby, 1999), on average a share $s = 0.714$ of car trips are shorter than 10 kilometres, while the rest can be considered "long distance trips". There is however no basis for assuming that benefits are distributed in a similar way, and absolutely no basis for distributing the fixed car costs among regional and long distance trips in a similar proportion.

Nevertheless, we do know something. We can safely assume that when the cost of owning a car is increased, those holding on to their cars suffer a monetary loss equal to the cost increase, while on average, those getting rid of their cars suffer a loss of half this amount. The losses of the first group cannot be reduced by changing trip behaviour, while the losses of the latter group does entail a change of mode for most of their trips, and will in part already have been captured in the benefit calculations of the regional trips. This group will save all their fixed car costs, while incurring a loss of benefits by their change to other modes for their regional and long distance trips. We know from their behaviour that they prefer this situation to the situation where they keep their car. The situation is illustrated in Figure 4.2.

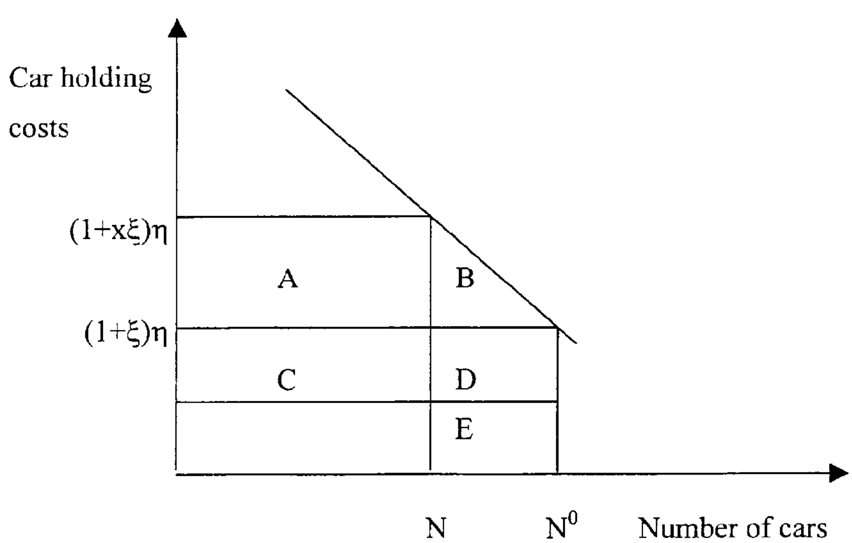

Figure 4.2.

Initially, fixed car costs are $(1+\xi)\eta$, where η is the pre-tax cost and ξ is the tax rate. The tax is then increased to $x\xi$ by way of the policy instrument x. Car ownership falls from N^0 to N. Those retaining their cars incur the loss –A. Assuming no other instruments are changed, they travel as before and get the same benefit from their trips. The revenue to the government is C + D initially and A + C afterwards, so the revenue increase is A – D.

Next we turn to those who sell their cars. Initially, they have a gross benefit in the travel markets of $U_r^0 + U_l^0$, say, where U_r^0 is the benefits of their local trips (over and above the benefit they could derive from using other modes), and U_l^0 is the benefit from long distance trips (over and above the benefit they could derive from using other modes). We know from their behaviour that $2B + D + E > U_r^0 + U_l^0 > D + E$, and so approximately, $U_r^0 + U_l^0 \approx B + D + E$. Their net benefit of owning a car is approximately B, and so –B is what they loose by the tax increase. This consists of the loss $U_r^0 + U_l^0$ less the saved fixed car costs D + E.

Assuming that $U_r^0 = s^*(U_r^0 + U_l^0)$, we note that the loss of U_r^0 must have been included in the regional user benefits u_r as calculated in section 4.2.3. To avoid double-counting, we do not add this part to the regional user benefits. Consequently, the total user benefits from a strategy that raises the car tax but keeps other instruments at their current levels can be approximated by

$$\begin{aligned} u &= u_r - A - (1-s)(B+D+E) + D + E \\ &= u_r - A - (1-s)B + s(D+E) \\ &= u_r - s(A-D-E) - (1-s)(A+B) \\ &= u_r - s(A-D) + sE - (1-s)(A+B) \end{aligned} \tag{4.6}$$

We note that all of the areas *A, B, D, E* can be expressed by the data ξ, η, N^0 and x and the car ownership model output *N*. Thus, to the extent that the car ownership model reflects the true behaviour of the residents of the Oslo area when faced with changes in the car tax, the things we need to do to get a consistent evaluation of u is to use the estimate of s and compute u_r and the areas *A, B, D* and *E* from the model output.

We assumed that $sE = (1-s)(A + B)$. Thus we used $u = u_r - s(A - D)$ (see the last line of the formula). This perhaps unfortunate choice was due to the time constraint when the study was performed. It may be noted that $A - D$ is the change in car tax revenue from the base case, or ΔJ as it was called earlier in this section.

The same formula should apply if the car tax is used together with other local instruments, as none of them affect car ownership according to our model, and all effects of using them should be measurable as effects on u_r. However, the situation with respect to the fuel tax is different. This is the only instrument beside the car tax that has an effect on car ownership and on long distance trips (directly and through its effect on car ownership).

We assume that a raise in the fuel tax can be depicted as a shift in the demand for cars, as shown in Figure 4.3.

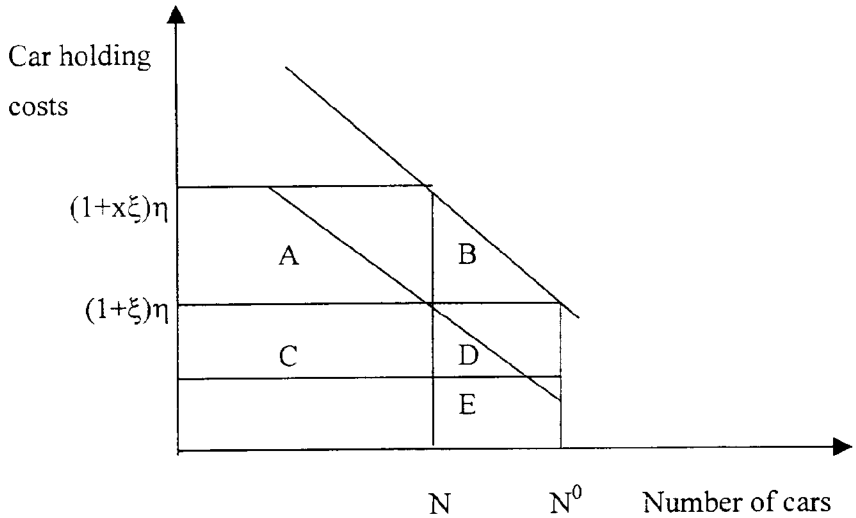

Figure 4.3.

In this case too, fixed car costs of $D + E$ are saved. But now both those holding on to their cars and those selling them will incur a loss in the travel markets due to the fuel tax increase. Of this loss, u_l cannot be assessed, and so the question arises if the diagram of the market for cars can help us assess u_l in an approximate way.

It must still be the case that for those who sell their cars, the gross benefit lost in the car market, $B + D + E$, equals the net benefits lost in the transport markets, $U_r^0 + U_l^0$. The regional part of these lost benefits has already been measured in the regional transport markets. Therefore, a share $s(B + D + E)$ must be deducted to avoid double counting. The difference from the preceding situation is only how those holding on to their cars are affected. When the car tax was increased, they suffered a loss of –A. When the fuel tax is increased instead, their losses are entirely in the transport markets.

As a group, would they be willing to pay A to get back to the original prices in the transport markets? We shall assume that they would. Thus the calculation of u is the same in the fuel tax case as in the car tax case.

Obviously, all of these loose arguments will have to be studied further and improved upon in a formal model. This is set aside for future work.

4.2.6 Net financial benefits of transport suppliers and the government

This two next sections describes the net financial benefits $f = f_t + f_g$ (as compared with the do-minimum scenario), where f_t denotes financial benefits of the transport suppliers and f_o denotes financial benefits of the government.

4.2.7 Transport suppliers

The net financial benefits of transport suppliers are denoted by

$$f_t = \Delta h + \Delta k + \Delta j + \Delta q + \Delta g + \Delta c$$

The net financial result for operators of parking facilities in the alternative scenario, h^n, relative to the *base* scenario, h^0, is

$$(4.7)\quad \Delta h = h^n - h^0 = \sum_k \sum_m \sum_j \left(x_{4k}{}^n \pi_{jmk} T^n_{kmj} - x_{4k}{}^0 \pi_{jmk} T^0_{kmj} \right),$$

where π_{jmk} is the parking fee at destination j at time k of the day for mode m and x_{4k} is the policy variable for the relative change in parking fee in period k as compared with π_{jmk}. The number of trips to destination j by mode m in period k, T_{kjm}, and the parking fee $x_{4k} \cdot \pi_{jmk}$ is calculated by the transport model. The net operating cost of parking facilities' operators (NOK/day) is $\Delta k = k^n - k^0$, which is set at zero.

The net financial result of road pricing and toll schemes operators is

$$(4.8)\quad \Delta j = j^n - j^0 = \sum_k \sum_m \sum_i \sum_j \left(x_{3k}{}^n \mu_{ijmk} T^n_{ijmk} - x_{3k}{}^0 \mu_{ijmk} T^0_{ijmk} \right),$$

where μ_{jmk} is the toll charge that is paid to enter inside the toll cordon for trips between origin zone i and destination zone j at time k of the day for mode m, and x_{3k} is the policy variable for relative change in toll charges as compared with μ_{jmk}. The number of trips between origin i and destination j by mode m in period k, T_{kijm}, and the toll charge $x_{3k} \cdot \mu_{jmk}$ is calculated by the transport model. The net operating cost per day of road pricing and toll schemes, $\Delta q = q^n - q^0$, in 1995 is set at 71/365, million NOK per day (Årsberetning AS Fjellinjen, 1996).

Operators of public transport are Greater Oslo Passenger Transport Ltd., AS Oslo Sporveier and Norges Statsbaner (NSB). Their net financial result is

$$(4.9)\quad \Delta g = g^n - g^0 = \sum_i \sum_j \sum_m \sum_k \left(x_5^n \beta_{ijmk}{}^n T^n_{ijmk} - x_5^0 \beta_{ijmk}{}^0 T^0_{ijmk} \right),$$

where β_{ijmk} is the fare for trips by public transport between origin zone i and destination zone j at time k of the day for public transport mode m, and x_{5k} is the relative change in fare as compared with β_{ijmk}. The number of trips between origin i and destination j by mode m in period k, T_{kijm}, and fares, $x_5 \cdot \beta_{ijmk}$, are calculated by the transport model. The operating cost of public transport operators (NOK/day) is given by $\Delta c = c^n - c^0$. Here $c^n = \sum_k [(1 + x_1^n \varphi_m) u_k^n + (1 + x_2^n \chi_m) o_k^n]$, where x_1^n and x_2^n are policy variables for relative changes of fuel tax rate for mode m, φ_m, and the tax rate on distance dependent costs other than fuel per vehicle kilometre of mode m, χ_m, respectively. In the present version of the framework both φ_m and χ_m are set at zero for public transport. The coefficient u is the pre-tax fuel cost of public transport operators (NOK/day) and $o^n{}_k$ is the pre-tax other cost of public transport operators (NOK/day). The operating cost of public transport operators includes salary – and social cost and capital cost and operational cost. Frequency dependent costs include a part of the operational costs (distance dependent costs) plus salary- and social costs, f, and capital cost k. Let $u_k^n = a_k \cdot f \cdot x_{7mk} + b_k \cdot k \cdot x_{7mk}$, where x_{7m} is the policy variable for the relative change in frequency. By using the Year Reports for 1995 of the public transport operators, we found that *f* and *k* can be set at 1729.2 and 477.8 million NOK, respectively. We assume that 35 % of the kilometres dependent costs plus salary- and social costs, *f*, are due to peak traffic and that all capital costs, *k*, are due to peak traffic. This gives $a_{peak} = 0.35$, $a_{offp} = 0.65$, $b_{peak} = 1$ and $b_{peak} = 0$.

4.2.8 Government

The net financial benefits of the government is given by

$$f_g = \Delta i + \Delta p + \Delta r - \Delta J + \Delta G .$$

The net tax revenue from PT operators of the alternative scenario, i^n, relative to the reference scenario, i^0, is

$$(4.10)\quad \Delta i = i^n - i^0 = \left(x_1{}^n \varphi_m u^n + x_2{}^n \chi_m o^n - x_1{}^0 \varphi_m u^0 - x_2{}^0 \chi_m o^0\right),$$

where x_1 and x_2 are the relative change in fuel tax rate for mode m, φ_m, and the relative change in the tax rate on distance dependent costs other than fuel per vehicle kilometre, χ_m, respectively. Both φ_m and χ_m are zero for public transport modes.

For regional trips, the net revenue of changes in the fuel tax for private cars and the changes in other distance dependent car taxes are

$$(4.11)\quad \Delta p = p^n - p^0 = \sum_i \sum_j \sum_k \left[x_1{}^n \varphi_m \rho_m D_{ijm}{}^n T_{ijmk}{}^n - x_1{}^0 \varphi_m \rho_m D_{ijm}{}^0 T_{ijmk}{}^0\right]$$

and

$$(4.12)\quad \Delta r = r^n - r^0 = \sum_i \sum_j \sum_k [x_2{}^n \chi_m \sigma_m D_{ijm}{}^n T_{ijmk}{}^n - x_2{}^0 \chi_m \sigma_m D_{ijm}{}^0 T_{ijmk}{}^0],$$

respectively, where pre-tax fuel cost per vehicle kilometre on regional trips, ρ_m, was set at 0.21 NOK/km for cars, pre-tax cost other than fuel per vehicle kilometre, σ_m, was set at 0.29 NOK/km for cars, fuel tax rate, φ_m, was set at 3.0 NOK/km for cars and the tax rate on distance dependent costs other than fuel per vehicle kilometre, χ_m, was set at 0.23 NOK/km for cars. The distance from zone *i* to zone *j* at time *k* of the day for cars D_{ijmk} and the number of trips, T_{ijmk}, is calculated by the transport model.

We make the assumption that time dependent car taxes paid by car drivers are used in the region where the car driver lives. Thus, time dependent car taxes that are paid by citizens in the greater Oslo area are used in the greater Oslo area. Hence, in accordance with equation (4.5), we have that changes in government revenue as a consequence of altered time dependent car taxes is

$$(4.13)\quad \Delta J = J^n - J^0 = (x_6^0 N_c^0 - x_6^n N_c^n)(\xi_1 + \xi_2)\eta .$$

Congestion pricing (i.e. each traveller pays for the extra generalised cost that he/she causes to other travellers). The net financial result of congestion cost pricing is given by

$$\Delta G = \sum_i \sum_j \sum_k \sum_m \Delta G_{ijkm} .$$

Where the extra cost between the zones *i* and *j* that is due to congestion, ΔG_{ijkm}, is calculated by the transport model.

Fuel tax revenue of long distance trips are left out, as the cost-benefit analysis is intended to cover only regional trips. For completeness, however, it can be noted that for long distance trips, we have that the government's budget balance as affected by altered fuel tax is given by

$$(4.14)\quad \Delta p_l = (x_1^n D_{l,m}^n - x_1^0 D_{l,m}^0)\varphi_m \rho_{l,m},$$

where $\rho_{l,m}$ is pre-tax fuel cost per vehicle kilometre on long distance trips and $D_{l,m}$ is the total distance by car that is travelled on long distance trips by citizens in the greater Oslo area.

4.2.9 External costs

Our external cost indicator is the difference between external costs in the alternative scenario and the base scenario

$EC = EC^n - EC^0.$

Let $\gamma_{am'}$, $\gamma_{nm'}$ and $\gamma_{pm'}$ be the city specific costs of accidents, noise and pollution, respectively, per vehicle kilometre where mode, *m'*, can be car, bus, tramway, subway, train, boat and walk/bicycle. In order to determine these cost, national costs calculated by Eriksen and Hovi (1995) were fitted to the Oslo area by subjective means (Table 4.2). This gives total external costs (γ_{am}+γ_{nm}+ γ_{pm}) for each of the modes of 0.5175, 2.024, 1.8745, 0.41055, 0.4715, 0, 0 (NOK/vehicle km), respectively.

Thus, the present value of external costs in strategy number *n* becomes

$$(4.15)\quad EC^n = [\sum_{i=1}^{30} \frac{1}{(1+r)^i}] \cdot [\sum_i \sum_j \sum_m (\gamma_{am} + \gamma_{nm} + \gamma_{pm}) \cdot D_{ijm}^n].$$

where the vehicle kilometres per day by mode *m'* in strategy number *n* in the target year, $D^n_{ijm'}$, is calculated by the transport model.

Table 4.2. External cost (NOK/vehicle km) fitted to Oslo by subjective means based on corresponding national cost calculated by Eriksen and Hovi (1995).

	Pollution	Noise	Accidents
Car	0.23	0.058	0.23
Bus	0.92	0.345	0.759
Tram	0	0.403	1.472
Subway	0	0.403	0.411
Train	0	0.46	0.472

4.2.10 Systematic overview of elements in the cost-benefit analysis

Table 4.3 gives a systematic overview of the elements that are accounted for in the cost-benefit analysis.

The costs and benefits of the travellers decomposes in:

- *The net time dependent costs* (investments) of car owners in the region - $s \cdot \Delta J$
- *Net monetary benefits* for car drivers and public transport travellers in peak and off-peak periods

  and correspondingly for

- *Timesaving*

Investments and operating costs of government and local authorities are:

- *Investments for public transport operators* Δc (frequency dependent costs for public transport operators, which includes a part of the operational costs [distance dependent costs] plus salary- and social costs and capital cost),
- *Investments and operating costs in the parking sector* Δk.
- *Investments and operating costs of the toll scheme* Δq.
- *The revenue from time dependent car taxes*, ΔJ, and the present value of infrastructure investments, I.

The net financial benefit to transport suppliers and government decomposes into

- *Money savings for parking operators* Δh (revenue from parking),
- *Money savings for tolling companies* Δj (revenue from tolling) or revenue from congestion pricing ΔG.
- *Money savings for government* (revenue from time dependent ΔJ and distance dependent car taxes $\Delta p + \Delta r$),
- *Money savings for public transport operators* Δg (income through fares), and
- *Money savings for government* Δi (subsidies or tax revenues from public transport operators).

Finally, the value of

- *Environmental cost savings EC*

is also specified in the cost-benefit accounts.

Table 4.3. This table contains all elements in the cost-benefit analysis, which represent net present values relative to the base scenario. A shadow price of public funds of λ is applied to all changes in the government and local authority budget balances, through multiplication of all nominal cash flows by $1+\lambda$, assuming they will have to pay any transport company deficits

		Level of the instruments						
RUN NO.		Parking	Frequency	Road price	Fuel price	Car tax	Other instruments	
		peak/offp	peak/offp	peak/offp			peak/offp	
Xx		$x_{4,peak}/x_{4,offp}$	$x_{7,peak}/x_{7,offp}$	$x_{3,peak}/x_{3,offp}$	x_1	x_6		
		Travellers		**Operators**			**Government and external**	**Row sum**
Benefit or cost category		peak trips	off-peak trips	PT	Parking	Toll		
Investment and operating costs		$-s \cdot \Delta J$		$(1+\lambda)\cdot\Delta c$	$(1+\lambda)\cdot\Delta k$	$(1+\lambda)\cdot\Delta q$	$(1+\lambda)\cdot(\Delta J+I)$	
Money savings,road		$UBC_{r,car}^{peak}$	$UBC_{r,car}^{offp}$		$(1+\lambda)\cdot\Delta h$	$(1+\lambda)\cdot(\Delta j+\Delta G)$	$(1+\lambda)\cdot(\Delta p+\Delta r)$	
Money savings,PT		$UBC_{r,pt}^{peak}$	$UBC_{r,pt}^{offp}$	$(1+\lambda)\cdot\Delta g$			$(1+\lambda)\cdot\Delta i$	
Financial benefits								
Time savings, road		$UBE_{r,car}^{peak}$	$UBE_{r,car}^{offp}$					
Time savings, PT		$UBE_{r,pt}^{peak}$	$UBE_{r,pt}^{offp}$					
Time savings, walk&cycle		$UBE_{r,w/b}^{peak}$	$UBE_{r,w/b}^{peak}$					
External cost savings							*EC*	
Total benefit								*W*

5 Optimisation of the social efficiency function

The social efficiency function W defined in the previous chapter is the sum of consumer surpluses for car and public transport travellers, the net economic benefits of operators and the government, and external costs. When there is no constraints on the available pricing instruments, the social efficiency function attains its maximum if and only if prices are set equal to marginal social costs. "No constraints" in this case is taken to mean that a charge can be levied on each and every link in the road network at no cost of implementation. The set of link charges that maximises the social efficiency function in this case is called first-best road pricing or a first-best solution.

A second-best solution can be found by raising or lowering the overall levels of available policy instruments in a way that maximises the social efficiency function W, i.e., to multiply current charges or taxes by optimised policy variables. One of the policy instruments for second-best pricing is a charge that can be levied only on a small sub-set of the links (e.g. the links traversing the present toll cordon). We may use of one or more of a set of instruments that were set at fixed levels in the first-best case, namely the area-wide level of parking charges, the fuel tax and annualised car taxes. As pointed out in Chapter 3, this means that the *setting* of our second-best scenarios is broader than the setting of our first-best scenario. If the second-best prices were lumped and compared with the first best prices, it could be then that the second-best instruments covers marginal cost that are not covered by the link based first-best prices. We have for instance in our scenarios that our first best solutions do not account for the marginal costs with respect to the number of car owners, whereas the medium-term second best solution with the fuel tax and annual car tax as available instrument does. Thus, comparison of link based first-best and medium term second-best solutions will be skewed.

However, the first-best solution in the rather narrow setting will still be very useful as a benchmark case against which the various *second-best* solutions can be judged. How far in the direction of the theoretical first-best solution are we able to move, when constrained by the pricing instruments actually available to planners and politicians? Although it is hard to imagine how first-best road pricing could be implemented in practice, it is perfectly possible, at least for the zero shadow price of public funds case, to describe and evaluate such a situation with the aid of a network assignment model.

In the rest of this chapter, we derive methods that can be used to determine first- and second-best solutions. An obvious way to obtain second-best solutions is to use a general optimisation algorithm to find the maximum of W with respect to the available instruments. For the first-best solution, the available instruments are the individual road charges for each network link. It is not feasible to use a general optimisation algorithm to optimise this many variables.[8] Instead we have to find an analytical expression for the road charges that can be added to the volume-delay functions on the network links.

5.1 First-best road pricing

In order to use the RETRO model for simulation of first-best road pricing, we add an expression for the marginal link-based costs $\frac{d\, c_a(q_a)}{d\, q_a} \cdot q_a$ to the volume delay functions. This method has been used in transport modelling for decades and works out fine as long as the shadow price of public funds is ignored or set to zero. In this Chapter, we describe how we incorporated a nonzero shadow price of public funds in the first-best solution.

The structure of the RETRO model was briefly explained in section 4.1.3. It consists of sub-models for the calculation of travel demand and transportation costs. A nested logit model calculates travel demand, and the transportation costs are calculated in the assignment algorithms of EMME/2. The transport costs c_a of driving from start to end on a link a can be subdivided in distance dependent costs d_a and a volume-delay function $t_a(q_a)$ for time costs with respect to traffic volume on link a . EMME/2 represents all costs in terms of time costs. Hence, a conversion factor w is used to transform distance dependent costs to time costs,

$$c_a(q_a) = t_a(q_a) + w \cdot d_a$$

where $c_a'(q_a) > 0$ and $c_a''(q_a) > 0$ and the conversion factor w is consistent with the parameter values in the conditional indirect utility functions of RETRO. The auto assignment algorithms include the volume-delay functions for all links in a real network representation, representing the time it takes to drive from the start to the end of the link.

Optimisation with respect to the social efficiency function W can be seen as a bilevel programme, where the lower level programme secures equilibrium in the transport model and the upper level program maximises W subject to this condition among others. If the transport model equilibrium is unique, we can replace the lower level programme with its Kuhn-Tucker conditions to get a single constrained optimisation problem. This line of attack might throw some light on the appropriate

[8] In an interesting paper, Yang and Bell (1997) studies a bilevel optimisation problem that can be solved to determine optimal link charges on all links in the presence of both queues and congestion. Our social efficiency function can be seen as a combination of two of their objective functions for the upper-level problem. Their lower-level problem is virtually the same as the one we solve each time we find the equilibrium in our transport model. Their proposed solution algorithm is very similar to the one we use for second-best optimisation. However, they do not show that it will work when all links are charged in networks of realistic size. We doubt very much that it will.

modifications needed in the link cost functions to take account of the shadow price of public funds in first-best marginal cost pricing.

Let the elements of the OD matrix be indexed by w, the links be indexed by a and the routes available for travel on the relation w be indexed by r_w. The set of these routes is R_w. The set of all routes, R, is indexed by r. The demand vector is $\boldsymbol{N} = (\ldots, N_w, \ldots)$, and the inverse demand functions are $\boldsymbol{D}^{-1}(\boldsymbol{N}) = (\ldots, D^{-1}{}_w, \ldots)$. The flow on link a is q_a, and the cost of using link a is $c_a(q_a) + b_a$, where c_a includes the time costs and b_a is the link charge. Furthermore, there is a given environmental cost e_a of traversing link a. The route flow vector is $\boldsymbol{f} = (\ldots, f_{wr}, \ldots)$. The Kronecker delta $\delta^a{}_{wr}$ is 1 if link a belongs to route rw, and 0 otherwise. Consider the following mathematical programme, where the welfare function W becomes a simplified version of the full efficiency function *EEFP*:

$$\underset{\mathbf{N},\mathbf{b},\mathbf{q},\mathbf{f}}{Max}\; W(\mathbf{N},\mathbf{b},\mathbf{q},\mathbf{f}) = \sum_w \int_0^{N_w} D_w^{-1}(y)dy - \sum_w D_w^{-1}(N_w)N_w + \sum_a q_a\left((1+\lambda)b_a - e_a\right)$$

s.t

$$N_w - \sum_{r\in R_w} f_{rw} = 0 \qquad \forall w \quad (\alpha_w)$$

$$\left(D_w^{-1}(N_w) - \sum_a \left(c_a(q_a) + b_a\right)\delta_{rw}^a\right) f_{rw} = 0 \quad \forall rw \quad (\beta_{wr})$$

$$D_w^{-1}(N_w) - \sum_a \left(c_a(q_a) + b_a\right)\delta_{rw}^a \le 0 \qquad \forall rw \quad (\gamma_{wr})$$

$$q_a - \sum\sum f_{rw}\delta_{rw}^a = 0 \qquad \forall a \quad (\pi_a)$$

$$N_w > 0, f_{rw} \ge 0, b_a \ge 0 \qquad \forall w, rw, a$$

The objective function is our social efficiency function. The two first terms are the consumer benefits, while the last term is the benefits to government less the environmental costs. As usual, $\lambda \ge 0$ is the shadow price of public funds. We optimise with respect to link charges and transport demand and flows. The constraints are the necessary and sufficient conditions for a user equilibrium in the network model, assuming there is a non-zero demand on all w. The Lagrangian multipliers for each of the four types of constraints are indicated at the right of the corresponding constraints.

The Kuhn-Tucker conditions for this problem can be written:

$$\text{(A)}\quad (1+\lambda)b_a + \frac{\partial c_a}{\partial q_a}\sum_w \sum_{r\in R_w}(\beta_{rw} f_{rw} + \gamma_{rw})\delta^a_{rw} - \pi_a \le 0 \ \ (= 0 \text{ if } q_a > 0)$$

$$\text{(B)}\quad \alpha_w + \sum_a \pi_a \delta^a_{rw} - \beta_{rw}\left(D^{-1}_w(N_w) - \sum_a (c_a(q_a) + b_a)\delta^a_{rw} \right) \le 0 \ \ (= 0 \text{ if } f_{rw} > 0)$$

$$\text{(C)}\quad \alpha_w = -\frac{\partial D^{-1}_w}{\partial N_w}\left(N_w + \sum_{r\in R_w}(\beta_{rw} f_{rw} + \gamma_{rw}) \right)$$

$$\text{(D)}\quad (1+\lambda)q_a - \sum_w \sum_{r\in R_w}(\beta_{rw} f_{rw} + \gamma_{rw})\delta^a_{rw} \le 0 \ \ (= 0 \text{ if } b_a > 0)$$

$$\text{(E)}\quad \gamma_{rw} \ge 0 \ \ (= 0 \text{ if } D^{-1}_w(N_w) \le \sum_a (c_a(q_a) + b_a)\delta^a_{rw})$$

Consider one particular link where $q_a > 0$ and assume $b_a > 0$. Then there is equality in (A) and (B), and by using these two equations we immediately have:

$$\text{(5.1)}\quad b_a = q_a \frac{\partial c_a}{\partial q_a} + \frac{1}{1+\lambda}\cdot(e_a + \pi_a)$$

The problem with this result is that π_a is an unknown shadow price. We do not even know the sign of it. We do not get any further than this by considering one link in isolation, nor does it seem possible to involve the literally thousands of relations compressed into (A) - (E).

To get further we let $q_{a,w}(r)$ represent the demand for trips on link a for group w. The number of travellers from each group w, $q_{a,w}$, can differ, but we must have that $q_a = \sum_w q_{a,w}$, where q_a is the total number of travellers on link a. Then, for each group w, there are separate expressions $\left(\frac{1}{q_{a,w}} \int_0^{q_{a,w}} q^{-1}_{a,w}(r)\,dr \right)$ for the willingness to pay per car driver to use link a. We let $r = g(x) = x \cdot \frac{q_{a,w}}{q_a}$. By substitution, total willingness to pay for using link a becomes

$$\sum_w \left(\int_0^{q_{a,w}} q^{-1}_{a,w}(r)\,dr \right) = \sum_w \left(\int_0^{q_a} q^{-1}_{a,w}(g(x))\cdot g'(x)\,dx \right) = \sum_w \left(\int_0^{q_a} q^{-1}_{a,w}(x\cdot \frac{q_{a,w}}{q_a})\cdot \frac{q_{a,w}}{q_a}\,dx \right).$$

Hence, $q^{-1}_a(x) = \sum_w \frac{q_{a,w}}{q_a}\cdot q^{-1}_{a,w}(x\cdot\frac{q_{a,w}}{q_a})$. Since the travel costs, $g_a(q_a)$, per traveller are the same for every group w, we must also have that $q^{-1}_{a,w}(q_a) = g_a(q_a)$ for all w, and thus $q^{-1}_{a,}(q_a) = g_a$. Hence, in a consistent way then $\sum_a \left(\int_0^{q_a} q^{-1}_a(r)\,dr \right)$ must be the total willingness to pay for using the road network, which is equivalent to the interpretation of $\sum_w \int_0^{N_w} D_w^{-1}(y)\,dy$. Thus the objective function of the optimisation problem can be reformulated as

$$\underset{\mathbf{N},\mathbf{b},\mathbf{q},\mathbf{f}}{\text{Max}}\ W(\mathbf{N},\mathbf{b},\mathbf{q},\mathbf{f}) = \sum_a \int_0^{q_a} q_a^{-1}(y)dy - \sum_a q_a^{-1}(q_a)q_a + \sum_a q_a\big((1+\lambda)b_a - e_a\big)$$

$$N_w - \sum_{r\in R_w} f_{rw} = 0 \qquad \forall w\ (\alpha_w)$$

$$q_a^{-1}(q_a) - c_a(q_a) - b_a \le 0 \qquad \forall a\quad (\gamma_a)$$

$$q_a - \sum f_{rw}\delta_{rw}^a = 0 \qquad \forall a\quad (\pi_a)$$

$$N_w > 0, f_{rw} \ge 0, b_a \ge 0 \qquad \forall w, rw, a$$

The Kuhn-Tucker conditions for this problem can be written:

(A') $\sum_{a'} \dfrac{\partial q_{a'}^{-1}}{\partial q_a}\cdot q_a + (1+\lambda)b_a - e_a + \left(\dfrac{\partial c_a}{\partial q_a} - \sum_{a'}\dfrac{\partial q_{a'}^{-1}}{\partial q_a}\right)(\gamma_a) - \pi_a \le 0\ \ (=0 \text{ if } q_a > 0)$

(B') $\alpha_w + \sum_a \pi_a\delta_{rw}^a \le 0\ \ (=0 \text{ if } f_{rw} > 0)$

(C') $\alpha_w = 0$

(D') $(1+\lambda)q_a - (\gamma_a) \le 0\ \ (=0 \text{ if } b_a > 0)$

(E') $\gamma_a \ge 0\ \ (=0 \text{ if } q_a^{-1}(q_a) \le c_a(q_a) + b_a)$

The reason that α_w is zero is that the link between N_w and q_a is less explicit in this formulation of the problem. The fact that α_w is zero implies that $\pi_a = 0$.

Hence

$$b_a = \frac{\partial c_a(q_a)}{\partial q_a}\cdot q_a - \frac{\lambda}{1+\lambda}\sum_{a'}\frac{\partial q_{a'}^{-1}}{\partial q_a}\cdot q_a + \frac{1}{1+\lambda}\cdot e_a$$

To make the link charge independent of q_a^{-1} and thus possible to use as part of volum-delay functions, we "approximated" the optimisation problem by:

$$\underset{\mathbf{N},\mathbf{b},\mathbf{q},\mathbf{f}}{\mathit{Max}}\ W(\mathbf{N},\mathbf{b},\mathbf{q},\mathbf{f}) = \sum_a \int_0^{q_a} q_a^{-1}(y)dy - \sum_a \big(c_a(q_a)\cdot q_a + e_a\cdot q_a\big)$$

$$N_w - \sum_{r \in R_w} f_{rw} = 0 \qquad \forall w \quad (\alpha_w)$$

$$q_a^{-1}(q_a) - c_a(q_a) - b_a + \lambda \cdot b_a \leq 0 \qquad \forall a \quad (\gamma_a)$$

$$q_a - \sum f_{rw} \delta_{rw}^a = 0 \qquad \forall a \quad (\pi_a)$$

$$N_w > 0, f_{rw} \geq 0, b_a \geq 0 \qquad \forall w, rw, a$$

For $q_a \geq 0$

$$b_a = \frac{1}{1-\lambda} \cdot \frac{\partial c_a}{\partial q_a} \cdot q_a + \frac{1}{1-\lambda} \cdot e_a,$$

To model a situation in which such a charge has been imposed, we simply run a network assignment task in which, rather than t_a, we use the marginal social cost function $t_a + b_a$ as our volume-delay relationship. The generalised (private) unit cost of road use at traffic volume q_a on a given road link, a, and under this pricing rule becomes

$$(5.2) \quad G_a(q_a) = c_a(q_a) + \frac{1}{1-\lambda} \cdot \frac{\partial c_a}{\partial q_a} \cdot q_a + \frac{1}{1-\lambda} \cdot e_a,$$

where we have set F_a at zero and assumed that the present fuel tax E_a exactly cover all environmental costs other than congestion costs. Although the theoretical soundness of equation (5.2) for application with a non-zero shadow price is still is open to debate, we use it for both zero and non-zero shadow prices of public funds. For evaluation we use the simplified version of W for a zero shadow price and the full W for a non-zero shadow price. Although the formula is only an "approximation" in the case of a non-zero shadow price of public funds, it seemed to give results that must be somewhere close to the real optimum. For the case of a zero shadow price of public funds, the equilibrium solution generated will be interpretable as the system optimum under marginal cost road pricing, i e as the solution after the imposition of an optimal road charge.

5.2 Second-best road pricing

In general, by a second-best policy package we shall understand the optimal combination of policy instruments under constraints on the free use of some of these instruments. The constraints may be due to technology and implementation costs, legislation, political and institutional barriers, or something else.

These constraints may, of course, be defined in various ways, depending on the temporal and spatial horizon.

Consistent comparisons with the first-best solutions can only be made with respect to the simplified *W* function, where costs and benefits of the travellers and operators on other modes are not taken into account (see section 5.1). This means that for truly consistent comparisons, second-best solutions should be optimised with the simplified *W* function. However, final evaluation can be made with the full *W* function.

Second-best of several measures is obtained if the welfare function, *W*, is optimised with respect to overall levels on a selection of transport measures while simultaneously satisfying the equilibrium condition. In a network consisting of one link, the first-best and second-best are equivalent. In a real network situation, however, we expect significant differences.

An unconstrained algorithm that doesn't use derivatives (DUD) can be used. Algorithms of this type need to evaluate the *W* function for any levels on the selected transport measures. The Simplex algorithm for optimisation in multiple dimensions is an unconstrained algorithm that *Doesn't Use Derivatives* (DUD). The algorithm is described in Appendix I.

In order to evaluate the social efficiency function this way, it is necessary to use the transport model to obtain the equilibrium condition for any levels on the selected transport measures. The values on variables of the equilibrium solution are subsequently used in the cost benefit analysis for calculation of the social efficiency function, *W*.

6 Equity assessment principles

6.1 Measures of inequality

Lorenz curves and Gini coefficient values can be used to in investigate the impacts of road pricing on the income distribution. The Lorenz curve, due to Lorenz (1905)[9], relates the cumulative proportion of income units (x-axis) to the cumulative proportion of income received (y-axis), when units are arranged in ascending order of their income. It takes the form of a straight line through the origin with slope 1 (45-degree angle) if and only if all units in the population receive the same income. In all other cases the curve is a monotonously increasing, upward-bending line located beneath the straight line with a 45-degree angle. The lower the Lorenz curve, the more income is concentrated in the upper income brackets, and the less «equitable» is the distribution.

Formally, let x be an income variable with cumulative distribution function F and expected value

(6.1) $E(x) = \mu$.

The Lorenz curve is defined by

(6.2) $L(u) = \frac{1}{\mu}\int_0^u F^{-1}(t)dt \qquad (0 \le u \le 1),$

where

(6.3) $F^{-1}(t) = inf[x : F(x) \ge t].$

To fix ideas, we show – as an example – the Lorenz curve for Oslo and Akershus in the benchmark scenario (Figure 6.1). Income levels are grouped into 8 brackets, generally NOK 50 000 per annum wide. The lowest bracket runs from zero to NOK 99, while the uppermost bracket includes incomes from NOK 300 000 upwards.

As shown by the Lorenz curve, the lowest 40 per cent of the adult population earn only 10 per cent of the total income.

[9] For a more up-to-date treatment, see, e g, Kakwani (1977, 1980, 1987), Atkinson (1970), or Sen (1973).

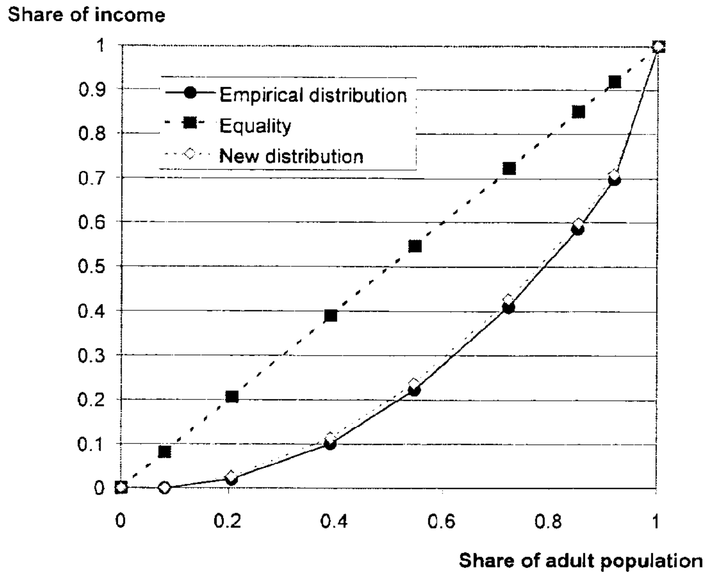

Figure 6.1. Lorenz curves for the adult population in Oslo and Akershus 1992. «New distribution» = NOK 10 000 annual increment for all.

Note, however, that this picture is conditioned by the fact that we use *individual* rather than *household* income. Many persons without low or zero income (students, housewives, etc) live in families with a fairly large household income. An analysis based on household income would most probably provide a less alarming picture of income inequality.

Thus, in the equity analyses based in the Oslo model, for which disaggregate data are available on household income as well as on individual income, we prefer to draw the Lorenz curves in terms of *household income per consumption unit*, defined as follows. Each household member is assigned a weight, equal to 1 for the household head (or the «first» adult person in the household, 0.7 for any additional adult and 0.5 for children up to 17. With small variations, these weights are in line with international (OECD) recommendations for household consumer surveys. The number of consumption units is given by the sum of the weights assigned to all members of the household.

When two distinct populations exhibit Lorenz curves such that one is uniformly located above the other, the former distribution (corresponding to the upper curve) is unambiguously more equitable.

However, if the two Lorenz curves intersect, one inevitably needs to «trade» one segment of the income scale against another, in order to conclude which distribution is «more equitable».

One way to summarise the information contained in the Lorenz curve is by way of the *Gini* coefficient, due to Gini (1912)[10], which is defined by

$$(6.4)\quad G = 2\int_0^1 [u - L(u)]du = 1 - 2\int_0^1 L(u)du,$$

i e as *twice the area between the 45-degree straight line and the Lorenz curve*. The higher the *Gini*-coefficient, the larger is the «gap» between the actual and the maximally equitable distribution, and the less «equitable» is – in a sense – the distribution at hand.

The *Gini* coefficient is bounded between zero and one: $0 \le G \le 1$.

In Figure 6.1, we also show – for purposes of illustration – the impact of a hypothetical NOK 10 000 increase in annual income for all individuals (except those with zero income), as measured in terms of the Lorenz curve. One notes that the area between the Lorenz curve and the straight line has been slightly diminished – indicating a certain improvement in the income distribution.

The diagram in Figure 6.1 can be made more easily readable by rotating the curves 45 degrees clockwise:

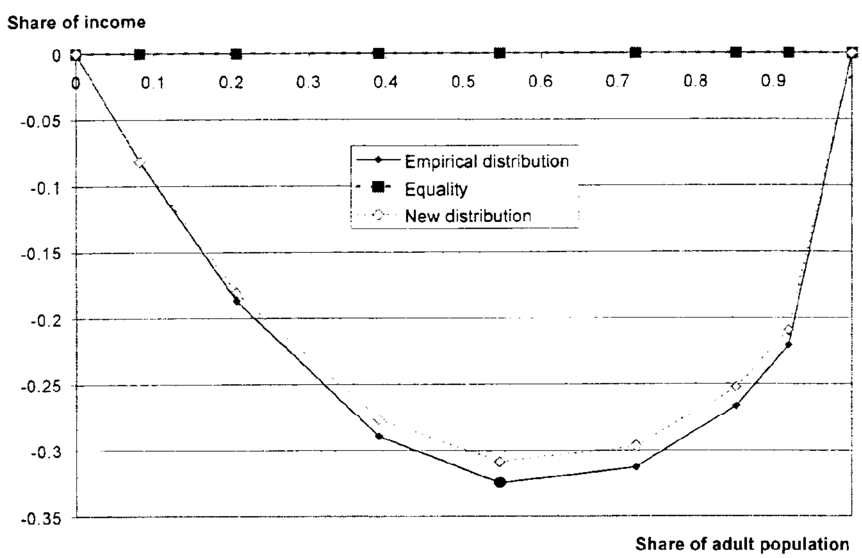

Figure 6.2. Rotated Lorenz curves for the adult population in Oslo and Akershus 1992. «New distribution» = NOK 10 000 annual increment for all.

[10] See also Dagum (1987) and references therein.

Here, the «perfect equality» Lorenz curve takes the form of a straight line along the horizontal axis.

In most cases, the interest is not in comparing some empirical distribution to an ideal «perfect equality», but rather to compare two plausible, real-world situations. To this end, a diagram in which the «new» distribution is compared to an «old» («empirical») would bring out the differences even more clearly, as in Figure 6.3.

Here, the old «empirical distribution» Lorenz curve takes the form of a straight line along the horizontal axis.

In the sequel, we shall apply this method of graphical illustration to show the equity impacts of the respective scenarios and of various ways of recycling the toll and tax revenue to the population.

We shall do this by first adding to the income of each bracket the monetary savings obtained by car drivers ($-s \cdot \Delta J + UBC^{peak}_{r,car} + UBC^{offp}_{r,car}$ in Table 4.1). Then – in this order – we add the money savings accruing to public transport users ($UBC^{peak}_{r,pt}$ + $UBC^{offp}_{r,pt}$), the time savings of car drivers ($UBE^{peak}_{r,car}$ + $UBE^{offp}_{r,car}$), the time savings of other travellers ($UBE^{peak}_{r,pt} + UBE^{offp}_{r,pt} + UBE^{peak}_{r,w/b} + UBE^{peak}_{r,w/b}$) and finally the toll and tax revenue redistributed to the tax payers according to some more or less progressive scheme.

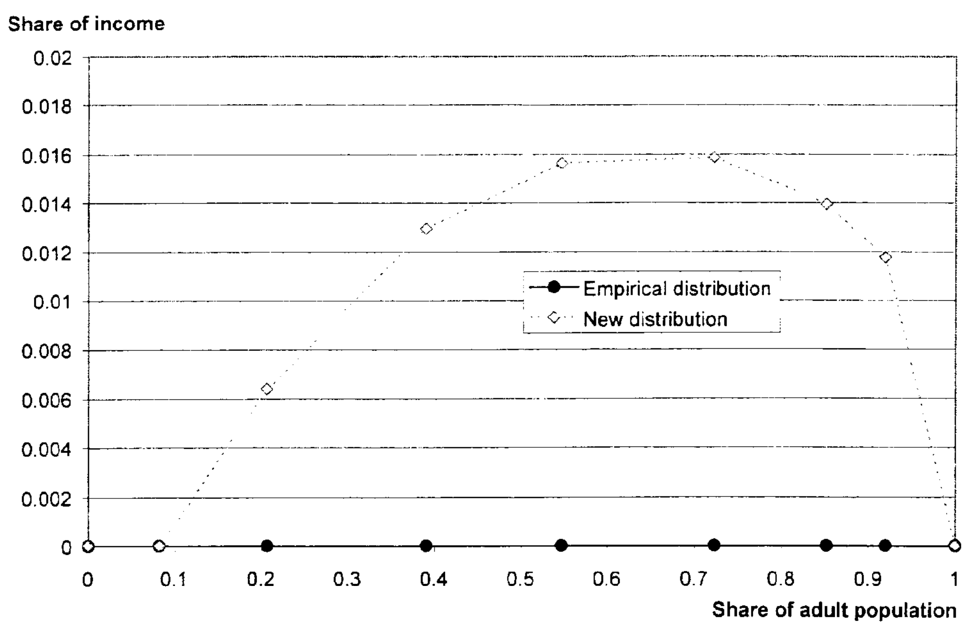

Figure 6.3. Lorenz curve differentials between the empirical distribution for Oslo-Akershus 1992 and a «new distribution» given by a NOK 10 000 annual increment for everyone.

In so doing, we make the simplifying assumption that this redistribution has only negligible feedback effects on behavioural choice. In a rigorous analysis, one would have to take into account that large income transfers will affect consumer behaviour, notably in the labour market, and to a considerable extent also the choices made in the transport sector, such as car ownership and use. Such an analysis would, however, require a full-fledged general equilibrium model of the urban economy, something which has been beyond the scope of this report.

In general, the income increments and transfers simulated in our analyses are small compared to the initial levels of income. Thus the assumption of negligible feedback is probably not too far-fetched.

It may be argued that it makes little sense to add together nominal gross income and some measure of consumer surplus, which includes all sorts of non-monetary benefits and utility components, such as time gains. In so doing, we implicitly define a kind of «*partial generalised income*», made up by the initial, nominal income and the consumer surplus *changes* generated by our policy. This is, of course, a simplified measure of welfare, in that the consumer surplus generated in the reference scenario is not included in the initial (generalised) income measure. We are therefore not able to say anything about the *relative* changes in welfare affecting the various income groups. However, as long as we restrict attention to *differential* effects on generalised income, the argument remains valid, if not at the ratio level of measurement, so at least on an interval scale.

6.2 A spatial equity analysis

Our methods of measuring and displaying income inequality were set out in section 6.1. This is to be applied to a population residing in 49 different zones of the urban area. Their gains and losses from a particular road pricing strategy depend on where they live. Thus it will not do to carry out a non-spatial equity analysis. If we could somehow determine the number of people in each household income group in each of the zones and their travel behaviour, the total net gains from a strategy for each income group could be determined as the sum of the net gains of the population in that income group in each of the zones.

To achieve this, we make use of the disaggregated nature of the transport model and the empirical data underlying it. Using household income per consumption unit as a "target variable", the sample is expanded to reproduce as closely as possible the observed mid-nineties population of each zone, in terms of its income distribution. These synthetical zonal populations are used in the transport model instead of the real populations, of which we only know their aggregate properties. By the transport model, we are now able to predict the travel choices of each income group in each of the zones and calculate the welfare effects for each of them. The weighted sum over zones of the net benefit of the households belonging to a particular income group will then be the net benefit of this income group.

The technique of forming synthetic zonal populations (so called prototypical samples) may be seen as a special variant of the sample enumeration technique described by Ben-Akiva and Lerman (1985), in which the respondents are weighted in such a way as to make the sample representative of any given zonal population. Details on our application of it can be found in Vold (1999). The use of prototypical samples to perform equity analyses of transport plans that take fully into account where the different income groups live, seems to be an innovative aspect of the present study.

7 Case City study

It is not possible with today's technology to implement link-based road pricing. Therefore first-best scenarios are primarily of interest as important benchmark scenarios. We can compare the efficiency of second-best policies and their corresponding first-best solution in order to investigate how close we can get to the social efficiency of a first-best solution with best practice second-best policies.

The framework for cost benefit analysis presented in chapter 4, with the real network transport model RETRO and the optimisation methods of chapter 5, can be used to obtain first-best and second-best solutions for road pricing strategies in the greater Oslo area (Oslo and Akershus counties). The method to obtain the first-best solution is found by adding an expression for the optimal link charge (see equation 5.2) to the volume-delay functions on each road link in the network representation as described in section 5.1. For the second-best solution, we use the Simplex algorithm as described in section 5.2 and in Appendix I. It is run until the changes in the transport measures between two iterations become small (i.e. until convergence is achieved). Usually 60 function evaluations is enough to get sufficiently close to achieve convergence with 4-5 policy variables. This takes approximately 90 hours on an HP9000 (D270) UNIX computer.

This chapter presents results from calculations of optimal road pricing strategies in different scenarios with respect to efficiency (the social efficency function W) and equity. Different schemes for redistribution of revenue from road pricing are used in scenarios with shadow prices of zero and 0.25.

Car ownership changes over time, but in the short-term we assume that car ownership is not affected by changes in the transport measures. Some scenarios are simulated with fixed car ownership and some scenarios are run with the car ownership model activated. The former scenarios may describe short-term effects, and the latter describe medium-term effects in the sense that car drivers have adjusted their car ownership according to the expenses of owning and driving a car. This implies that we can find the optimal levels of the measures in the short run without recalculation of car ownership, whereas in the medium run the car ownership model recalculates car ownership.

Hence, the scenarios differ with respect to whether the road pricing strategy is first-best or second-best, they differ with respect to the measures at our disposal for optimisation, whether the shadow price of public funds is set at zero or 0.25, whether the scenario is short- or medium-term, and with respect to the choice of scheme that is used for redistribution of the revenue from road pricing.

7.1 The base scenario

The base scenario describes the transport network in greater Oslo in the middle of the 1990s. Prices, taxes and car ownership also correspond to the situation in the greater Oslo area at that time, except that the charge at the toll ring is set to zero. The population in the different parts of the city is represented at a disaggregated level in terms of a prototypical sample. The prototypical sample[11] is based on available data from a travel survey (Vibe, 1991) and statistical information of the number of people in eight different household income groups of December 1992 in different parts of the city.

All measures available for optimisation are connected to a policy variable. In the description of the *W* function in Chapter 4, the policy variables for the base scenario are denoted x_{3k}^0 for the toll charges, x_2^0 for the fuel tax, x_{4k}^0 for the parking charges in peak and off-peak and x_6^0 for the time dependent car taxes. Other policy variables include x_1^0 for distance dependent taxes other than fuel tax, x_5^0 for public transport fares and x_7^0 for public transport frequency.

In the base scenario, the policy variables, $x_1^0, x_2^0, x_4^0, x_5^0$, x_6^0 and x_7^0 (Table 3.1) were set to 1, whereas the policy variable for toll charges, x_3^0, was set to zero.

The total number of trips consists of elastic and inelastic demand. The elastic demand is calculated endogenously by RETRO, and the inelastic demand is given as fixed OD matrices. The inelastic demand consists of trips from places that are not covered by the detailed road network representation in the model (i.e. from outside the greater Oslo area) and trips related to air flights. The total inelastic demand in the peak period of the base scenario comprises 14.2% of the total number of car trips in the region, and the total inelastic demand in the off-peak period of the base scenario comprises 5.8% of the total number of car trips in the region.

For the base scenario and also all the alternative scenarios, separate model simulations are made for one hour in the peak period and one hour in the off-peak period. We assume that the peak period lasts 4.34 hours and that the off-peak period lasts 12 hours. Hence the number of trips, total distances etc. in the peak and off-peak periods are multiplied by 4.34 and 12 hours, respectively.

The average travel time for the slow mode is based on an exogenously given speed of 1 km per 12 minutes (i.e. 5 kms/hour). Most trips by bicycle are faster. Anyway,

[11] The prototypical sample that we use is based on data from a travel survey that contains a random sample of the population in Oslo and Akershus in 1990 and 1991. The sample includes 3057 records with information about one individual and the household he/she belongs to in the region. To obtain the prototypical sample, the records were grouped in eight household income groups. Each group was assigning to a weight, such that multiplying the number of occurrences of individuals in the groups by the corresponding weights gives the number people in household income groups according to statistical information of 1992. A more detailed explanation of how the prototypical sample was generated is described in Vold (1999).

the speed of the slow mode is not used in any other calculations. The monetary distance dependent cost of driving one kilometre by car is set at NOK 1.20.

Table 7.1 and 7.2 summarises results from a transport model simulation of the peak and off-peak period of the base scenario, from which we derive that the average monetary cost of one kilometre by public transport is 0.99 NOK in peak periods and 1.02 NOK in off-peak periods. Simple algebraic operations on the results show that the average trip lengths by car, public transport and slow mode in the peak periods are 20.04, 16.27 and 8.58 (kms), respectively, and the average travel times are 27.31, 48.8 and 103.0 minutes per trip. The average trip lengths by car, public transport and slow mode in the off-peak periods are 18.4, 14.7 and 12.3 (kms), respectively, and the average travel times are 21.1, 50.8 and 148.1 minutes per trip.

Table 7.1. Results from model simulation of the peak period (4.34 hours) of the base scenario

All trips	**727 656**
Trips by car	**399 165**
Trips by public transport	**226 188**
Trips by slow mode (walk/bicycle)	**102 302**
Total number of cars in the area	**390 522**
Total parking cost on trips by car originating in zones inside the region (NOK)	**1 204 803**
Total parking costs on trips by car originating outside the region (NOK)	**114 002**
Total toll charged for car trips and crossing the toll ring (NOK)	**0**
Total toll charges for car trips originating outside the region and crossing the toll ring (NOK)	**0**
Total fares (NOK)	**3 655 015**
Total distance by car (km)	**8 001 032**
Passenger distance by public transport (km)	**3 680 714**
Walk and bicycle distance (km)	**877 729**
Total vehicle distance by tramway (km/hour)	**694**
Total vehicle distance by train (km/hour)	**2 908**
Total vehicle distance by buss (km/hour)	**10 243**
Total vehicle distance by boat (km/hour)	**42**
Total vehicle distance by subway (km/hour)	**1 233**
Total travel time for cars (minutes)	**10 902 624**
Total travel time for cars originating outside the region (minutes)	**4 105 029**
Total passenger travel time by public transport (minutes)	**11 038 452**
Total travel time by walk and bicycle (minutes)	**10 532 756**

Parking fees are charged in the city centre of Oslo, in some adjacent zones and at particular points (shopping centres etc.) in the municipalities of Akershus. The fees are set at NOK 4.94 and 2.44 per hour. Since most trips in the peak period are work trips, the parking period is considered to be eight hours long. According to Table 7.1, the average parking cost per kilometre by car in the peak period is NOK 0.15.

In the off-peak periods the fees are set at 8.86 or 2.94 NOK per hour. The parking time in the off-peak period is assumed to be 2 hours per trip. Based on Table 7.2, the average parking cost per kilometre by car is NOK 0.07.

Table 7.2. Results from model simulation of the off-peak period (12 hours) in the base scenario

All trips	827 378
Trips by car	646 407
Trips by public transport	103 350
Trips by slow mode (walk/bicycle)	77 619
Total number of cars in the area	390 522
Total parking cost on trips by car originating in zones inside the region (NOK)	833 219
Total parking costs on trips by car originating outside the region (NOK)	13 198
Total toll charged for cars that cross the toll ring (NOK)	0
Total toll charges for cars originating outside (extern) of the region that cross the toll ring (NOK)	0
Total fares (NOK)	1 558 291
Total distance by car (km)	11 890 640
Passenger distance by public transport (km)	1 522 533
Walk and bicycle distance (km)	957 703
Total vehicle distance by tramway (km/hour)	751
Total vehicle distance by train (km/hour)	1 863
Total vehicle distance by buss (km/hour)	3 956
Total vehicle distance by subway (km/hour)	926
Total travel time for cars (minutes)	13 643 961
Total travel time for cars originating outside the region (minutes)	2 336 206
Total passenger travel time by public transport (minutes)	5 252 258
Total travel time by walk and bicycle (minutes)	11 492 441

7.2 Alternative Scenarios

The alternative scenarios differ from the base scenario in that a first-best strategy or a second-best strategy of road pricing is applied.

We will consider two scenarios with first-best road pricing strategies, eight scenarios with second-best road pricing strategies and two scenarios that are considered "acceptable" according to a survey accomplished in the EU project AFFORD. We consider only road pricing measures. To fix fares at current levels is debatable. However, the fares are not easily changed, due to a link to the national level of railway fares (the Railway Company requires compensation from local authorities to go under the national fare level) and due to tight local transport budgets.

In the first-best scenarios the travel costs including road charges on the network links can expressed by equation (5.2). It was pointed out in chapter 5 that the expression for road charges at the network links does not take account of user benefit for travellers by public transport or costs and benefits for parking operators and public transport operators. These effects are considered to be minor as compared to the effects of the shadow price of public funds, the fuel tax and environmental costs that are taken into consideration.

The two first-best scenarios differ with respect to the value of the shadow price of public funds. The second-best scenarios also differ with respect to the value of the shadow price of public funds, and with respect to the selected policy variables that are optimised (Table 7.3).

Table 7.3. Short description of the model scenarios we have analysed. Assumed shadow prices in scenarios with scenario names starting with P and S are zero and 0.25, respectively.

Scenario	Description
P11/S11	First-best solution.
P21/S21	Optimal levels of toll- and parking charges separate for periods of peak and off-peak traffic load.
P22/S22	Optimal levels on a package of measures consisting of toll – and parking charges separate for the peak and off-peak periods and a fuel tax. The scenario is considered short-term as the car ownership model is inactivated.
P22b/S22b	Same as P22/S22, except that optimal levels on the measures are considered medium-term as the car ownership model is activated.
P22c/S22c	Same as P22b/S22b, but time dependent car taxes is added to the package of optimised measures.
P3/S3	Scenarios considered acceptable among the travellers.

The two first-best scenarios are denoted S11 and P11, where the shadow price of public funds is set at 0.25 and zero respectively. Correspondingly, the shadow prices is set at 0.25 in the second-best scenarios S21, S22, S22b and S22c, and at zero in P21, P22, P22b and P22c. The second-best scenarios differ with respect to the road pricing measures that are available for optimisation. Toll charges and parking charges in periods of peak and off-peak traffic load are optimised in all scenarios. No other measures are optimised in the scenarios S21 and P21, but fuel tax is available for optimisation in S22, P22, S22b, P22b, S22c and P22c. In scenarios S22c and P22c time dependent car taxes is also a policy variable. The two "acceptable" scenarios are denoted S3 and P3. They differ only with respect to the shadow price of public funds, which is set to 0.25 and zero, respectively.

The car ownership model calculates the car ownership in the scenarios S22b, P22b, S22c, P22c, S3 and P3. For the rest of the scenarios, car ownership is equal to car ownership in the base scenario.

The measures available for optimisation in the P21 and S21 scenarios are toll charges and parking charges in periods of peak and off-peak traffic load. We categorise both toll charges and parking charges as regional measures. This means that local authorities can set the value of the measures. The car ownership model does not depend on these regional measures. Hence, the P21 and S21 scenarios can only be simulated with fixed car ownership.

The P22 and S22 scenarios are similar to P21 and S21 except that the fuel tax is added as a measure available for simultaneous optimisation. Fuel tax is a national measure to which the car ownership model is responding. Car ownership is fixed in P22 and S22. As we let car ownership be the same as in the base scenario, this implies that P22 and S22 are optimal in the short-term only, i.e. the car owners have not had the time to reconsider their status of car ownership.

The scenarios P22b and S22b include optimisation of the same measures as in P22 and S22. In contrast, however, car ownership is adjusted by invocation of the car ownership model. The scenarios differ in that P22 and S22 describe short-term optimal charges with car ownership fixed, whereas P22b and S22b describe medium-term optimal charges where car drivers adapt their car ownership to the fuel price. The medium-term optimal charges were found by connecting the car ownership model for calculation of car ownership with respect to the fuel tax. Remember that toll charges and parking charges are not variables in the car ownership model and therefore do not affect car ownership in the analyses.

Like scenarios P22b and S22b, P22c and S22c invoke the car ownership model, and the scenario is therefore considered medium-term.

As the car ownership model (Ramjerdi and Rand 1992) does not respond to changed toll and parking charges, we must make the assumption that car ownership is not affected by these charges in the medium run. The car ownership model is capable, however, of calculating car ownership with respect to the national level on fuel tax and on the national level on time dependent car taxes. Hence, we connect the car ownership model to the transport model in simulation of scenarios where we want to calculate the medium-term effects of national fuel tax and national car tax on car ownership.

The road pricing measures in the S3 and P3 scenarios are not optimised but set at values considered "acceptable" according to a survey accomplished as part of the EU project AFFORD.

For optimisation of the second-best solutions with a shadow price of public funds of zero we used a simplified W function where changes in user benefits for travellers by public transport and changes in costs and benefits for parking operators and public transport operators are not taken into account. This ensured consistency in a comparison between the first-best and second-best scenarios. However, in the second-best optimisations, it would have been possible to take account of the public transport consumer and producer surpluses in the optimisation and evaluation, thus making these solutions the second-best solutions in a broader setting than the one defined for first-best optimisation.

For evaluation, the full W was used for all scenarios with a shadow price of 0.25.

7.3 Results from analyses of the social efficiency of marginal cost road pricing

In this section we present results from the scenarios with first-best and second-best road pricing. This includes optimal values on the road pricing measures, the overall social efficiency of the scenarios and surpluses for the main categories: (1) travellers, (2) operators and government, and (3) the environment, which suffers external costs in terms of accidents, pollution and noise. For all scenarios we give details about the (1) travellers' timesaving, (2) travellers' monetary savings and (3) public revenue surplus that can be used for redistribution.

Then, we look at the resources used up or saved in the scenarios: (1) monetary benefits, (2) time benefits, (3) external costs in terms of accidents, pollution and noise and (4) the resources saved in the economy as indicated by the shadow price of public funds.

We also present the effects of road pricing on travel behaviour. This includes effects on (1) trip frequency by mode, (2) trip length, (3) travel demand and (4) travel speed.

More details and supplementary results are found in Appendix II where the maximised full or simplified W function are decomposed and presented according to Table 4.3 for all scenarios. Appendix II also contains Table AII.13 where changes in travel behaviour relative to the business-as-usual scenario is presented subdivided by peak and off-peak.

7.3.1 Optimal values of road pricing measures and efficiency subdivided by main category

The packages of road pricing measures available for optimisation in the scenarios are quite different. In the first-best scenarios the only type of measure is the link-based road charge. Toll charges and parking charges for periods of peak and off-peak traffic load are subject to optimisation in all the second-best scenarios. The fuel tax and annualised time-dependent car taxes are also available in some second-best scenarios.

The optimal values of the policy variables are highly dependent on the composition of the packages and the shadow price of public funds. Optimal tolls and fuel tax increase unambiguously as the shadow price of public funds increases. For all scenarios, the optimal value of the *off-peak toll* policy variable is zero for a zero shadow price of public funds and above one for a shadow price of public funds of 0.25 (Table 7.3). Hence, the effect of the shadow price of public funds on the optimal toll charge is particularly high for off-peak periods. The optimal fuel tax and peak toll charges are also quite sensitive to the shadow price of public funds, whereas the effects on parking charges is moderate.

It is noticed (Table 7.3) that the optimal toll charges in the peak period in for instance the P22 scenario is 0.873 times the present one-way charge of 8.1 NOK. This means that if car drivers are charged on entering only, the optimal toll charge in this scenario becomes 13.56 NOK. The optimal toll charge in the off-peak period is zero, and the optimal fuel tax was 1.403 times that in the base case.

Table 7.3. Relative level of pricing instruments in 12 scenarios (see Table 7.3). The bold figures are policy measures that have been subject to optimisation in the respective scenarios. The actual optimised toll charges (NOK) are found by multiplying the optimal policy variables by 16.2 (NOK). The optimised parking charges, fuel tax and annualised car taxes were found by multiplying the respective policy variables by the charges that were used in base case (i.e. mid 1990s levels)

	Scenarios											
Optimised measure	P11	S11	P21	S21	P22	S22	P22b	S22b	P22c	S22c	P3	S3
Toll (peak)	0.0	0.0	**1.329**	**2.11**	**0.873**	**1.512**	**0.996**	**1.726**	**0.00**	**1.116**	0.5	0.5
Toll (off-peak)	0.0	0.0	**0.00**	**1.338**	**0.00**	**1.103**	**0.00**	**1.149**	**0.00**	**1.283**	0.5	0.5
Parking (peak)	1.0	1.0	**1.025**	**1.28**	**1.047**	**1.398**	**0.988**	**1.367**	**1.024**	**0.911**	1.6	1.6
Parking (off-peak)	1.0	1.0	**0.996**	**1.62**	**0.934**	**1.19**	**0.929**	**1.455**	**1.471**	**1.504**	1.6	1.6
Fuel tax	1.0	1.0	1.0	1.0	**1.403**	**2.662**	**1.293**	**2.015**	**0.814**	**1.594**	1.16	1.16
Annualised car taxes	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	**5.264**	**4.3**	0.85	0.85
Link charge	yes	Yes	no	no	no	no	no	no	no	no	no	no

The total efficiency of the different scenarios vary greatly (Figure 7.1). We are not only interested in the total efficiency, however. A scenario can have a very high social efficiency but at the same time it can be unacceptable to travellers. A strategy where the total efficiency is somewhat lower but the burden on travellers is more bearable is perhaps more likely to be implemented. To study this, the maximised social efficiency function *W* was split for all scenarios in net gains and losses for the travellers, the operators and the government, and the environment (Figure 7.1).

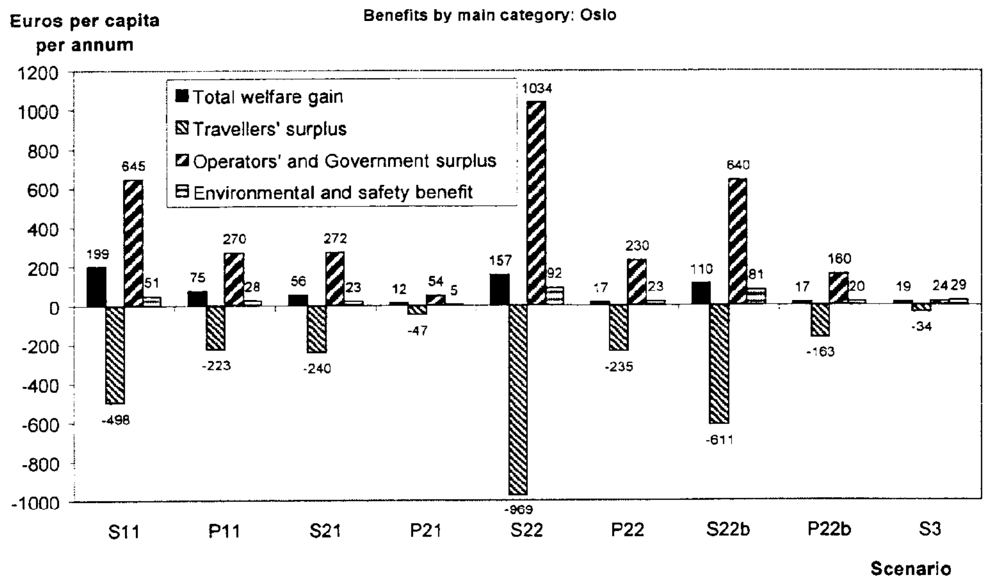

Figure 7.1. The total welfare gain W (i.e. net social efficiency) of the policy scenarios, and W split in net gains and losses for the travellers, the operators and the government, and the environment.

A general pattern is that scenarios with a shadow price of public funds of 0.25 produce much higher net benefits. The reason is that by valuing public revenue higher, a larger amount of public revenue can be collected before the marginal negative effect of road pricing on travellers' benefit becomes larger than the marginal utility of collecting one extra unit of public revenue.

Under the assumption that the shadow price of public funds is zero, the net social efficiency obtained from first-best link-based road pricing in Oslo and Akershus has been calculated at 75 *Euros per capita per annum* over a 30-year period (P11 in figure 7.1). Under the alternative assumption of a 0.25 shadow price of public funds, the overall benefit more than doubles, reaching 199 Euros per capita per annum.

The second-best solution under current institutions (*P21*) for Oslo invokes the use of (i) cordon toll charges (peak and off-peak) and (ii) parking charges.[12] It turns out that these instruments are rather inefficient compared to the ideal first-best policy *P11*. The overall welfare improvement in the *P21* scenario amounts to a mere *12 Euros per capita per annum*, or 16 per cent of the theoretically optimal («first-best») gain under zero cost of funds.

This rather discouraging result must, however, be interpreted with caution. We cannot rule out certain methodological explanations, such as the fact that our model specifies only two, rather crude travel time periods («peak» and «off-peak») and does not allow for substitution between them. Nor can we exclude the possibility that these results are strongly tainted by the particular traffic conditions in Oslo, notably by the location of the cordon toll ring, which is located such as to maximise revenue rather than to restrain the traffic, and by the fact the toll revenue has facilitated massive improvement in the road network, to a point where congestion is kept at a fairly moderate level.

When a 0.25 shadow price of public funds is assumed, the second-best policy under current institutions (*S21*) achieves a 56 Euro per capita annual benefit, or 28 per cent of the first-best solution.

Turning to the *S22/P22* scenarios (second-best after institutional reform), in which the fuel tax is allowed as a third policy instrument, welfare gains increase noticeably, especially under non-zero cost of funds (*S22*), in which case the benefit is seen to almost triple from the *S21* scenario. If the fuel tax does not have the distortionary effects of other taxes, and if it could be used as a purely local instrument, there are obviously large gains to society in setting it at more than twice the current level. However, this gain accrues mainly to the government and the environment, while travellers lose. The *P22* scenario, on the other hand, represents a mere 50 per cent improvement from *P21*, achieving no more than 23 per cent of the first-best benefit (*P11*).

The *S3* («acceptable») policy package for Oslo scenario makes little difference. An overall annual benefit of 19 Euros per head is generated – less than 10 per cent of the first-best solution – mainly because of the environmental and safety benefit, which amounts to 29 Euros per capita per annum.

As in the model tests in Edinburgh and Helsinki in the AFFORD project (Fridstrøm et al. 1999), almost all scenarios for Oslo and Akershus that are presented in this report are characterised by negative travellers' surplus before revenue recycling. Assuming, however, that the net public revenue flow (tax, toll, parking, and public transport operators' surplus) is somehow (and costlessly) redistributed to the private consumers, even the second-best solution would imply

[12] The term "under current institutions" means that only policy instruments currently available to local authorities are considered. Conversely, the term "after institutional reform" implies that instruments currently under the control of national authorities have been transferred to local authorities. The usefulness or indeed the possibility of a reform permitting, for instance, local fuel taxes, is not considered.

a certain welfare improvement for the travellers. In Figure 7.3 below, we compare the differential *resource costs and benefits* characterising the first-best and second-best scenarios. In this picture, we have let the money transfers between the private and the public sector cancel each other out, so that we are left with only true (non-pecuniary) utility and resource effects.

7.3.2 Travellers' time savings, monetary savings and public revenue surplus

The optimal road pricing strategies in all scenarios lead to large transfers of money from travellers to the government. There is a negative effect of road pricing on the consumer benefit in terms of increasing monetary costs for the travellers and reduced number of travellers. This is compensated by time savings. However, the travellers' surplus in Figure 7.1 shows that the net benefit is negative in all scenarios.

In Figure 7.2, we show private benefits (monetary and time benefits as well as their balance) after full public revenue recycling (i.e. it is assumed that all revenue is returned back to the consumers/households). The private benefit after public revenue recycling is defined as the public revenue minus the consumer surplus deficit before revenue recycling. Hence, if there is larger consumer surplus deficit before public revenue recycling than public revenue available for recycling, revenue recycling will not achieve full private compensation.

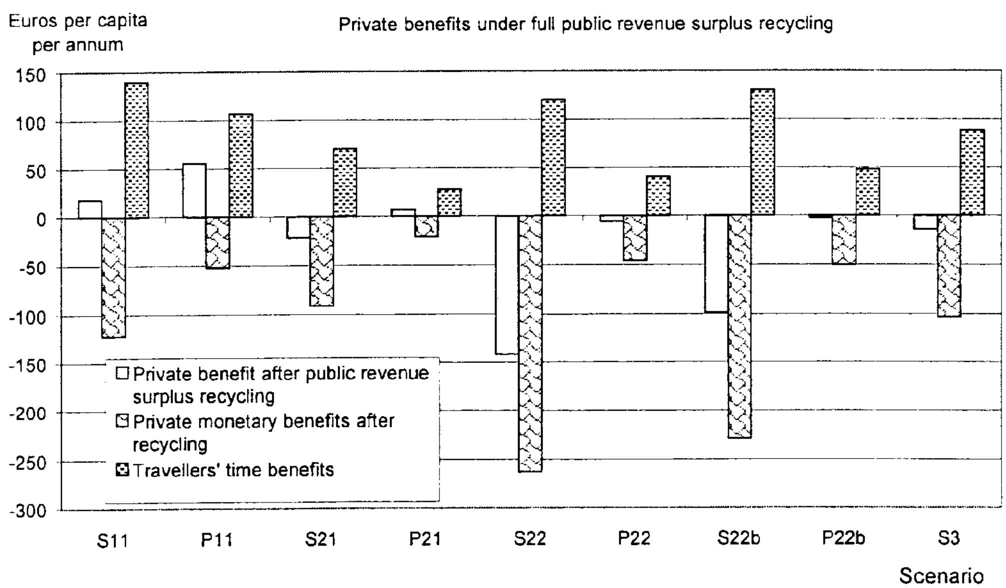

Figure 7.2. Private benefits under full public revenue surplus recycling.

We see that the private benefit after public revenue recycling is larger in the scenarios with a shadow price of public funds of zero than in the corresponding scenarios where the shadow price of public funds is 0.25. The reason is that public revenue is weighted by 1.25, which means that public money compensates for a larger dead-weight loss while maximising the *W* function.

For the first-best scenarios we see that private benefit after public revenue surplus recycling is higher in the scenario with a shadow price of public funds of zero. In both scenarios the timesaving and recycled money compensates for the extra road charges and reduced number of car trips.

One notes that when a particular (shadow) value is attached to public revenue *per se*, the socially optimal policy involves fairly heavy losses to private consumers, even after revenue recycling (*S22* and *S22b*). When no such extra value is assigned to public money, however, there is no point in squeezing out extra revenue from private consumers, and the optimal road charge is set at a level which leaves consumers just about equally well off after second-best pricing, given full revenue recycling.

7.3.3 Net gains and losses of resources

In Figure 7.3, we compare the differential *resource costs and benefits* characterising the first-best and second-best scenarios. In this picture, we have let the money transfers between the private and the public sector cancel each other out, so that we are left with only true (non-pecuniary) utility and resource effects.

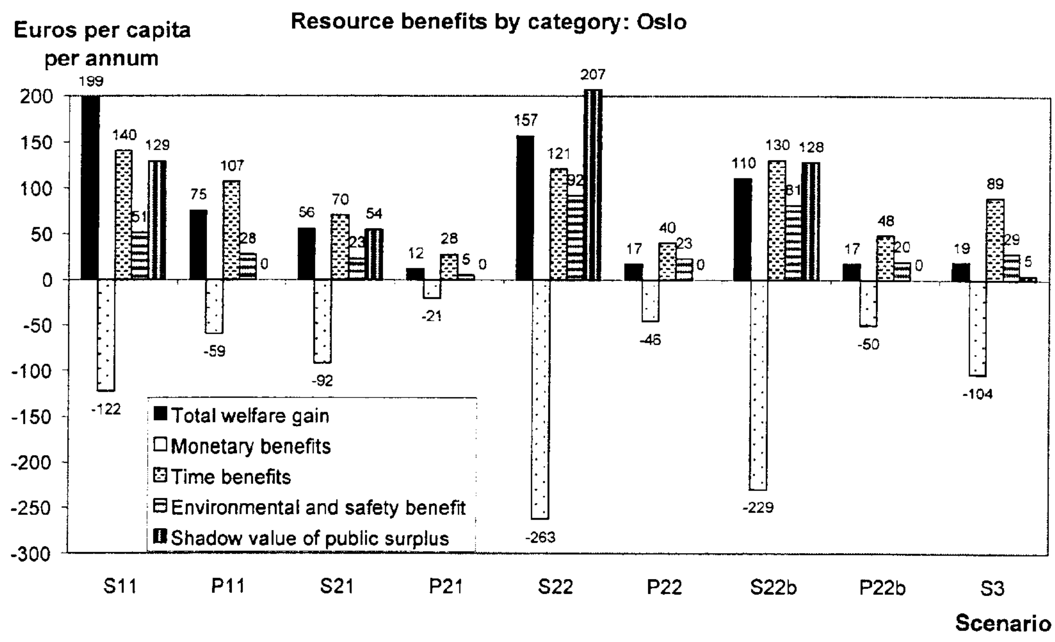

Figure 7.3. The total welfare gain W (i.e. net social efficiency) and W split according to resource benefits by category

One notes that, in all scenarios, the total welfare improvement decomposes into a *negative* monetary benefit and a *positive* time benefit.

Marginal cost road pricing has the double effect of *discouraging congestion* and *raising public revenue*. To the extent that public funds are a scarce resource, the latter effect may well be the more important as seen in a social efficiency perspective. This is at least the case in a less heavily congested city like Oslo.

This would, however, depend on how the road pricing revenue is used. If it is used to step down distortionary taxation somewhere else in the economy, or to extend the supply of a public good for which the willingness-to-pay exceeds the marginal cost of production, then a «double dividend» accrues. If, on the other hand, the revenue is redistributed to the private sector in a way that does not improve the incentive structure faced by economic agents, there is no extra dividend to be accounted for.

The use of a non-zero cost of public funds implicitly assumes that a double dividend somehow does arise.

A bit simplified, one might say that in Oslo, second-best marginal cost pricing is socially profitable first and foremost because it is – we assume – an attractive form of taxation. If, on the other hand, the marginal opportunity cost of public funds is *not* larger than zero, the benefit of marginal cost pricing is very substantially reduced.

Indeed, in the second-best scenarios *S22* and *S22b*, the benefit derived form the shadow value of public funds is larger than the overall benefit of the policy (Figure 7.3).

This point is further illustrated by a comparison between the *S22b* and *S22* scenario, and between *P22b* and *P22*. The *S22* scenario makes use of the fuel tax instrument, however without allowing households to reduce car ownership in response to rising costs of fuel. Thus, in this scenario, the pricing policy is, in a sense, «twisting the arm» of private households, squeezing out considerable tax revenue. The optimal fuel tax in this scenario comes out at +166 per cent, i e 2.66 times the current level. Parking charges are up by 40 and 20 per cent, and toll rates by 200 and 120 per cent in peak and off-peak periods, respectively.

In *S22b/P22b*, we allow car owners the time to get rid of their cars, in cases where the total annual cost of car ownership and use exceeds the utility derived from it. When the price of fuel goes up, a number of households may want to choose a consumption bundle including less car ownership and use.

When the cost of public funds is larger then zero, such an opportunity to evade the fuel tax clearly reduces the social profitability of marginal cost pricing (compare *S22b* to *S22*). Under the zero cost of funds, however, it does not matter much for the optimal solution whether the households are allowed to change their consumption of cars (compare *P22b* to *P22*).

7.3.4 Benefits by recipient category

In Figure 7.4, we show costs and benefits decomposed by recipient category. As noted earlier in this report the model also offers the opportunity to study the effect of optimising the annualised car taxes (i.e., *vehicle* taxes), in addition the toll, fuel tax and parking charge instruments. This is the content of the *S22c/P22c* scenario - «medium-term second-best after extended institutional reform». Thus, in Figure 7.5, we compare second-best scenarios with and without the use of the vehicle tax instrument. Recall that *S22b/P22b* («medium-term second-best after institutional reform») differs from *S22/P22* («short-term second-best after institutional reform») in that car ownership rates are allowed to change in response to increasing fuel price, and that *S22c/P22c* differs from *S22b/P22b* in that the vehicle tax instrument is invoked as well. Needless to say, also the *S22c/P22c* scenario allows for variable car ownership.

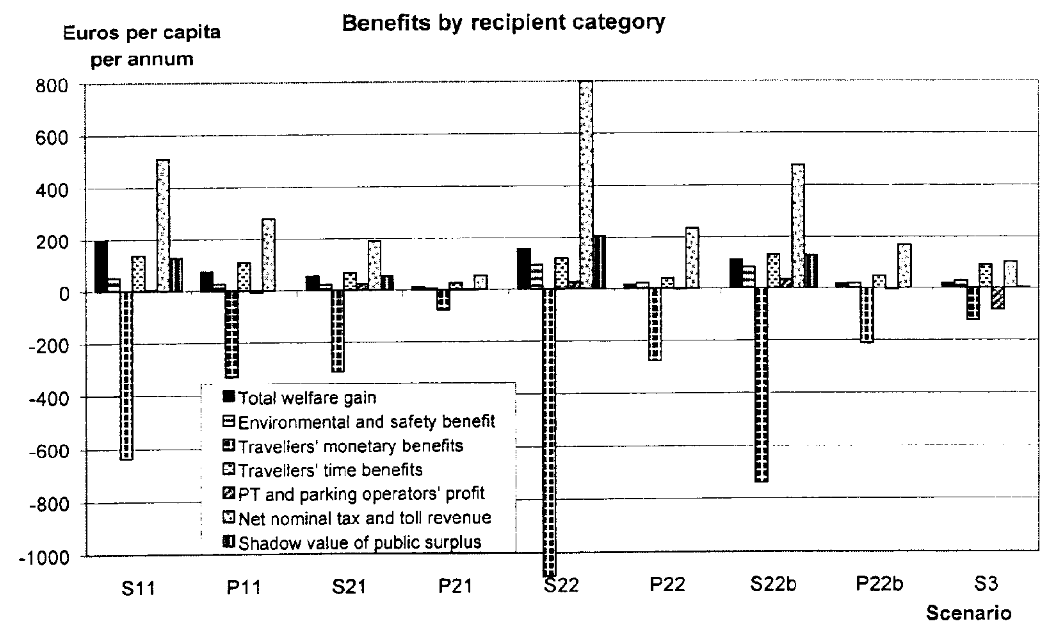

Figure 7.4. Benefits by recipient category.

The *S22c/P22c* scenario must, however, be interpreted with great caution, since it is not at all obvious how one should account for the utility of car ownership *per se*. The RETRO model for Oslo takes account of the utility derived from trips made inside the Oslo region only. But a large number of car trips are also made over longer distances. Thus, increased car ownership gives rise to an additional utility component not taken account of in the regional network model. In the cost-benefit analysis, an *ad hoc* procedure, based on the empirically observable split between short distance and long distance travel by car, is used to calculate this utility component and add it on to the consumer surplus measure derived from the regional network model (Chapter 4).

This essentially means that in the *S22c/P22c* scenario a rather different social efficiency function is optimised compared to the first-best scenario. Results are therefore not directly comparable with the first-best solution.

Yet, it is interesting to note the vehicle tax instrument seems to add substantially to the obtainable overall welfare gain and even to the time benefits accruing to travellers, although the cost is heavy in terms of overall traveller accessibility and cash expenditure. This is true even if the shadow price of public funds is set to zero.

Somewhat simplified, these results probably reflect the fact that car use in general is closely connected to car ownership, so that an effective way to combat excessive private motoring would be to curb car ownership.

In the *S22c* scenario, vehicle tax rates are up by 330 per cent, while the fuel tax increases by only 60 per cent, compared to 102 and 166 in the *S22b* and *S22* scenarios, respectively (Figure 7.5). When the marginal cost of public funds is zero (*P22c*), an even larger diversion of the tax burden, from car use to car ownership, appears optimal: here the vehicle tax is up by 426 per cent, while the fuel tax goes *down* by 19 per cent.

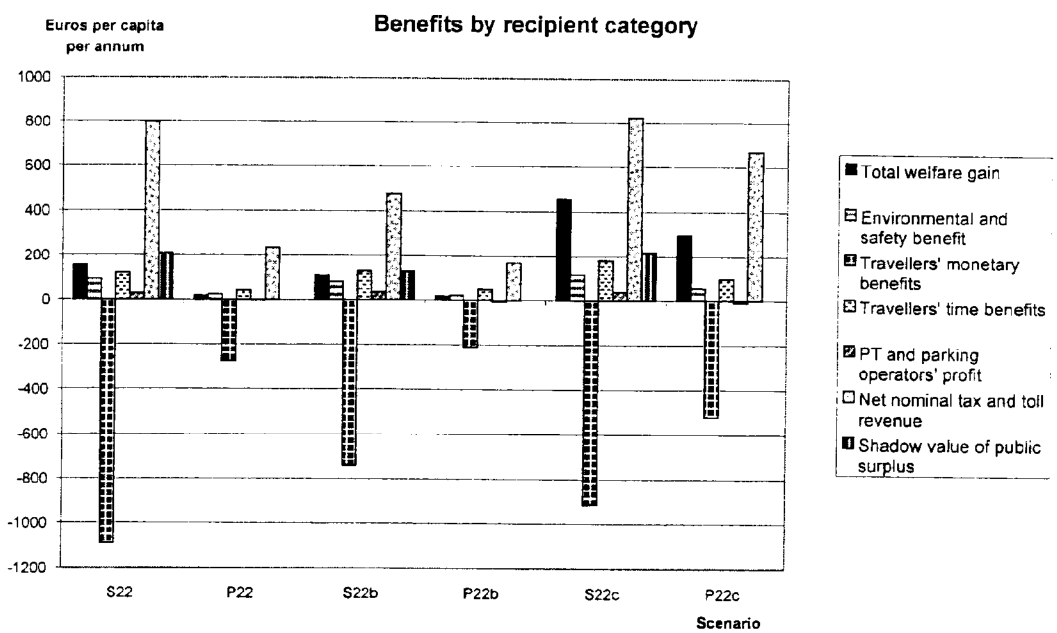

Figure 7.5. Second-best scenarios after institutional reform.

It should be noted, though, that vehicle tax increases of this order of magnitude, from the very high level already present in Norway, are entirely unrealistic and politically unthinkable, as they imply a more than 50 per cent cut in aggregate private car ownership.

The large vehicle tax in S22c and P22c imply that a smaller part of the population is still willing and wealthy enough to pay. However, among the most willing and wealthiest part of the population, the elasticity is much smaller than among the rest. Hence, in the case of S22c and P22c, the elasticity of car ownership with respect to the optimised level on the vehicle tax is much higher than in the base case.

Thus, the main point of the *S22c/P22c* scenario is to illustrate the following. Although, at first sight, the fuel tax may seem like a clearly more appropriate marginal cost instrument, since – at least under given technology – the charge increases roughly in proportion to the distance driven by each individual driver or vehicle, such a conclusion becomes less obvious in a wider (macroscopic) perspective. Here, the very rate at which the marginal member of the population decides to own and operate a car becomes highly relevant, since car ownership and use are strongly interrelated elements of behaviour. Therefore, the use of vehicle taxation as a second-best marginal cost pricing instrument is not nearly as inadequate a it may seem from a simplistic, microscopic line of reasoning, in which one fails to take into account the close *de facto* interrelationship between vehicle ownership and use.

7.3.5 Travel behaviour effects

The effects of marginal cost pricing on travel demand in Oslo are shown in Figures 7.6 through 7.9 and briefly discussed in the text below. Appendix II contains corresponding results for peak and off-peak periods (see Table AII.13).

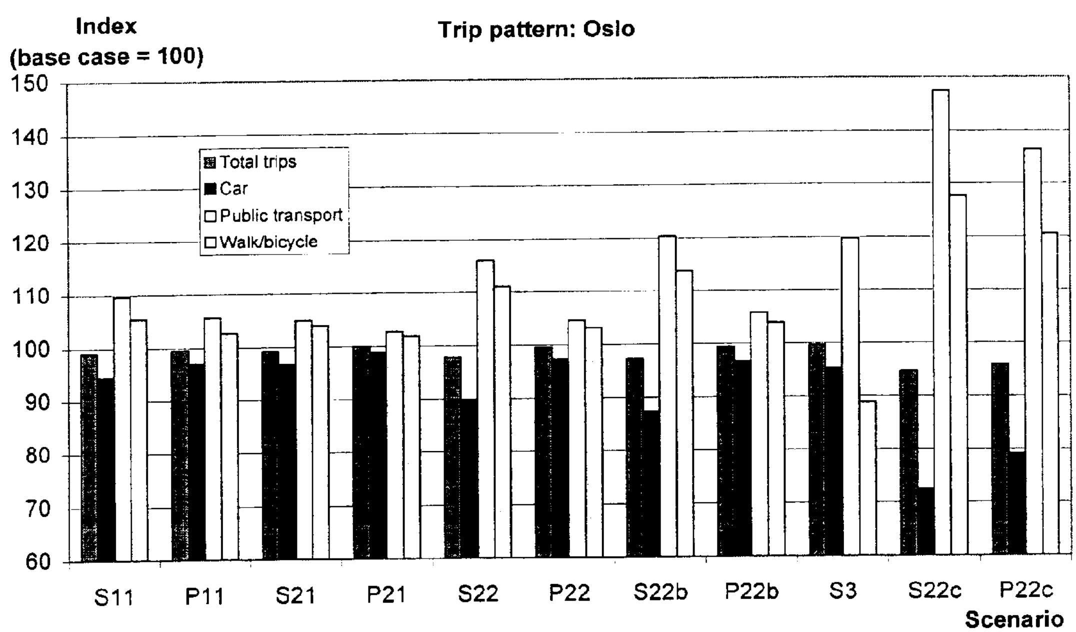

Figure 7.6. Impact of marginal cost pricing on trip frequency by mode.

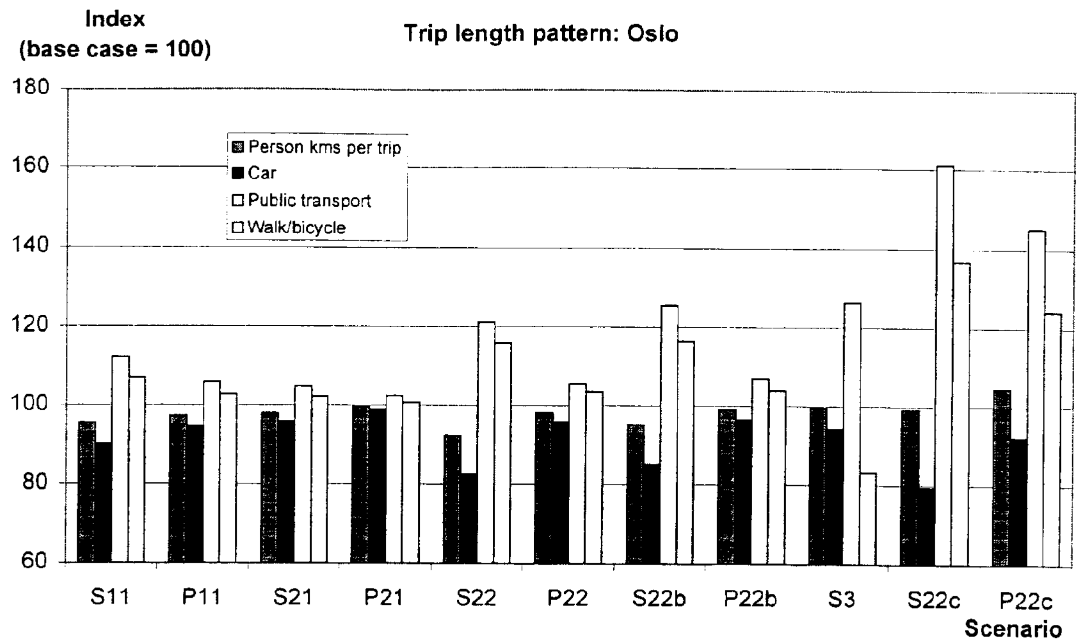

Figure 7.7. Impact of marginal cost pricing on average trip length by mode.

Most scenarios show a moderate transfer of trips form private cars to public transport. Only the unrealistic *S22c/P22c* package, by which most people get rid of their cars, achieves a massive change of mode (Figure 7.7).

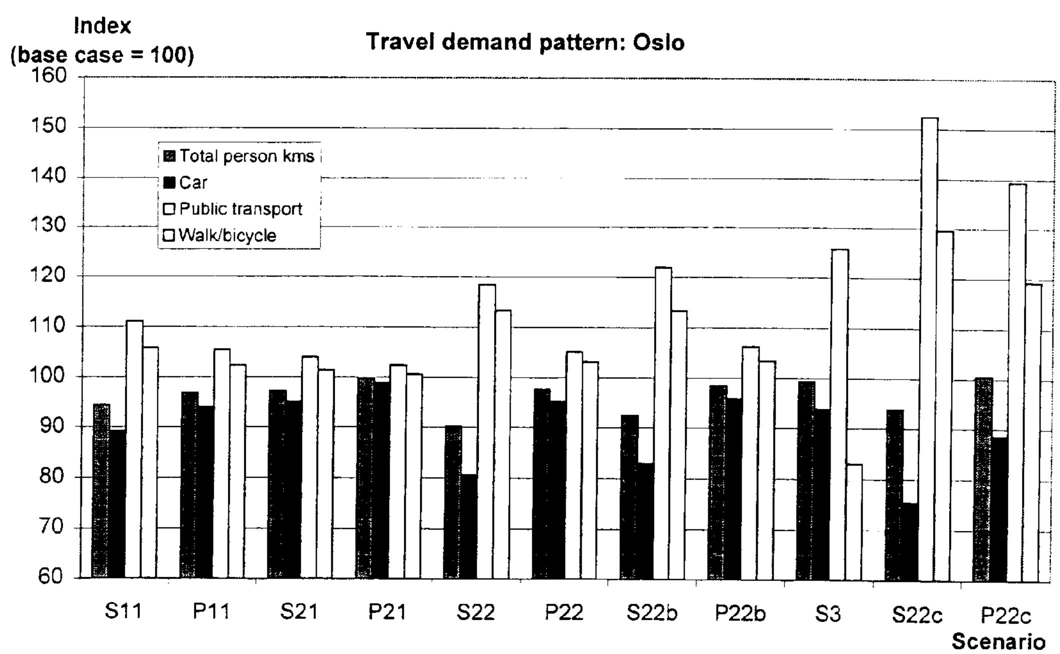

Figure 7.8. Impact of marginal cost pricing on person kilometres travelled, by mode.

Car trips generally become shorter, while public transport trips get longer (Figure 7.8).

Overall travel demand, as measured in vehicle kilometres, is down by up to 10 per cent in the second-best scenarios, while travel by car may drop as much as 20-25 per cent (Figure 7.8).

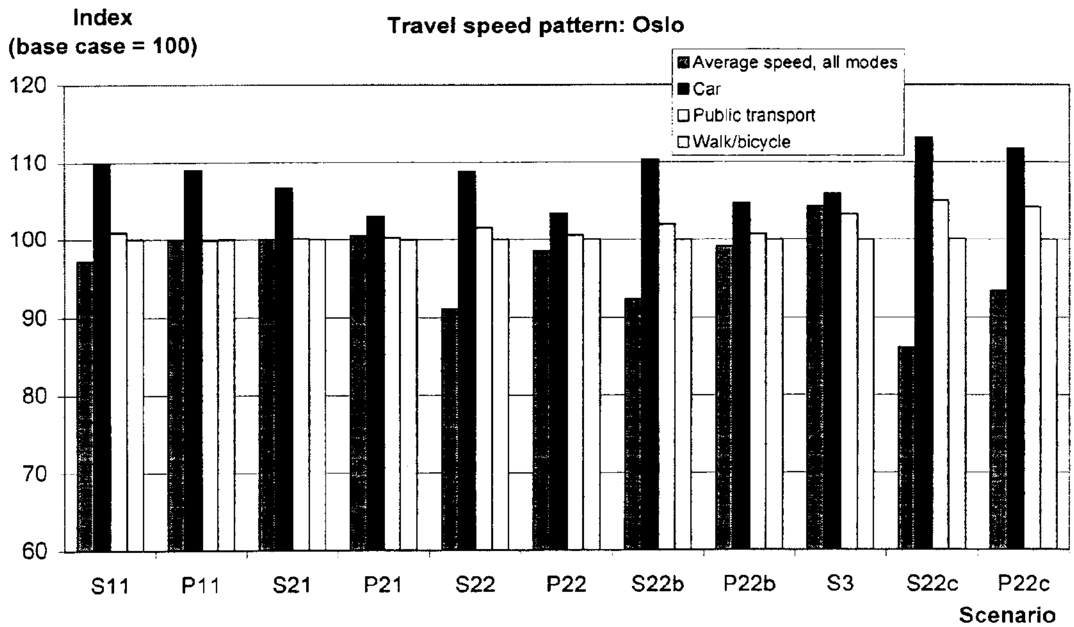

Figure 7.9: Impact of marginal cost pricing on travel speed by mode.

An interesting picture emerges when one computes the average speed of travel, overall and by mode (Figure 7.9). Although the speed increases within every mode as congestion is relieved, the overall mean speed goes down, on account of the shift from private cars to public transport, walking and bicycling.

7.4 Results of the equity analyses of marginal cost road pricing

The distributional aspects of marginal cost pricing are important. Road pricing inevitably affects different population groups differently, when it comes to out-of-pocket expenditure as well as in terms of accessibility and timesavings. Moreover, a most critical aspect appears to be the fact that road pricing inherently involves a cash flow from private consumers to a public authority or operator.

Thus the fact – demonstrated in the previous chapter – that road pricing may represent a very efficient form of taxation is hardly an asset in the eyes of the general public. It may seem that the acceptability of road pricing hinges crucially on whether the road pricing revenue can be used in a way that mitigates the hardship imposed in the first place.

Another common objection to the implementation of road pricing is that it will affect different residential zones in unfair ways, reducing the accessibility of some while possibly enhancing the travel opportunities of others.

In this section we shall deal with the effect on the income (re) distribution for a selection of the first-best and second-best scenarios that were specified in section 7.3.

7.4.1 The S11/P11 (first best) scenarios

A first impression of the equity impact of scenario *S11* is given in Figure 7.10. Income brackets are defined in terms of *household income per consumption unit* (see chapter 6), and the brackets are delimited in such a way that each group covers approximately one eighth of the adult population. That is, bracket 1 runs from zero income to the 12.5 income percentile, bracket 2 from the 12.5 to the 25th percentile, and so on.

Under the assumption that the public revenue from road pricing is not redistributed to private consumers, but kept by the public authority, all income groups suffer a welfare loss as measured by the change in consumer surplus.

In Figure 7.11, where the differential effects on «partial generalised income» (see last paragraph of section 6.1) are shown, this is brought out more clearly. Here, we have also added a last column representing the added net income accruing to all income groups if the revenue from road pricing is redistributed to the households in amounts proportional to each household initial income, i e as a *constant percentage point tax relief to all income earners.*

One notes that the monetary welfare loss incurred during the peak hour period, in terms of road charge expenditure and reduced amounts of travel, are larger in the higher income brackets (first column in Figure 7.11 – «Money savings peak added» – corresponding to items $UBC_{r,car}^{peak}$ and $UBC_{r,pt}^{peak}$ of Table 4.3). The more affluent people are to a larger extent hit by peak hour road pricing. The off-peak charges, however, are much more evenly distributed between income groups, so that when all monetary costs are summed up (as in the second column of Figure 7.11 – «All money savings added» – corresponding to items $UBC_{r,car}^{peak}$ and $UBC_{r,pt}^{peak}$ *plus* items $UBC_{r,car}^{offp}$ and $UBC_{r,pt}^{offp}$ of Table 4.3), the differences between income segments become less pronounced. Indeed, the third income bracket ends up incurring almost as large a monetary cost as the uppermost bracket.

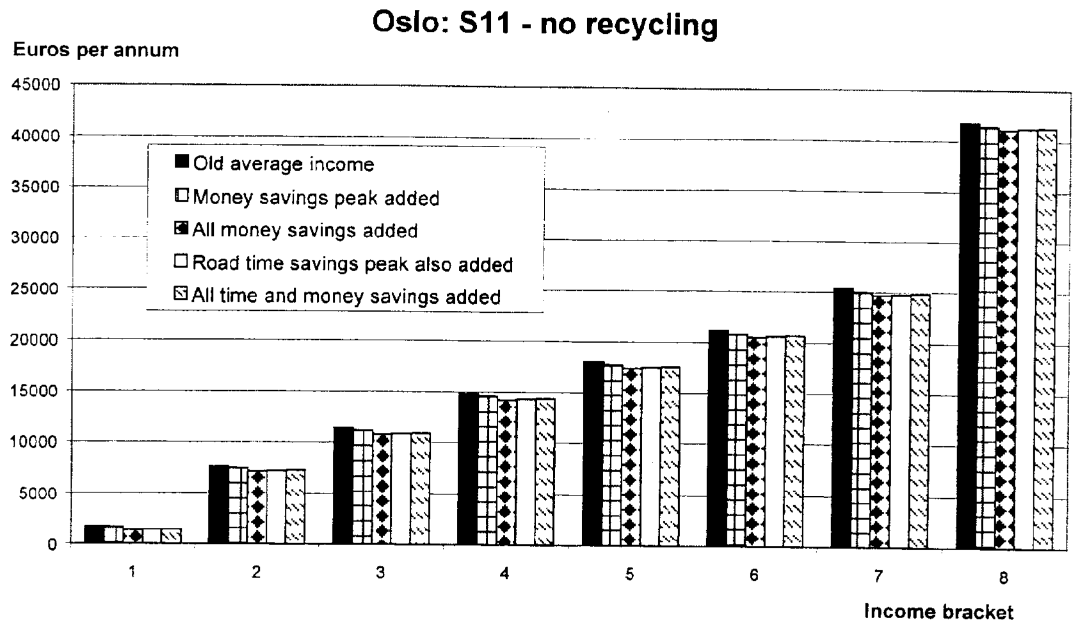

Figure 7.10. Effects of «first-best» marginal cost pricing by household income per consumption unit, assuming no recycling of revenue.

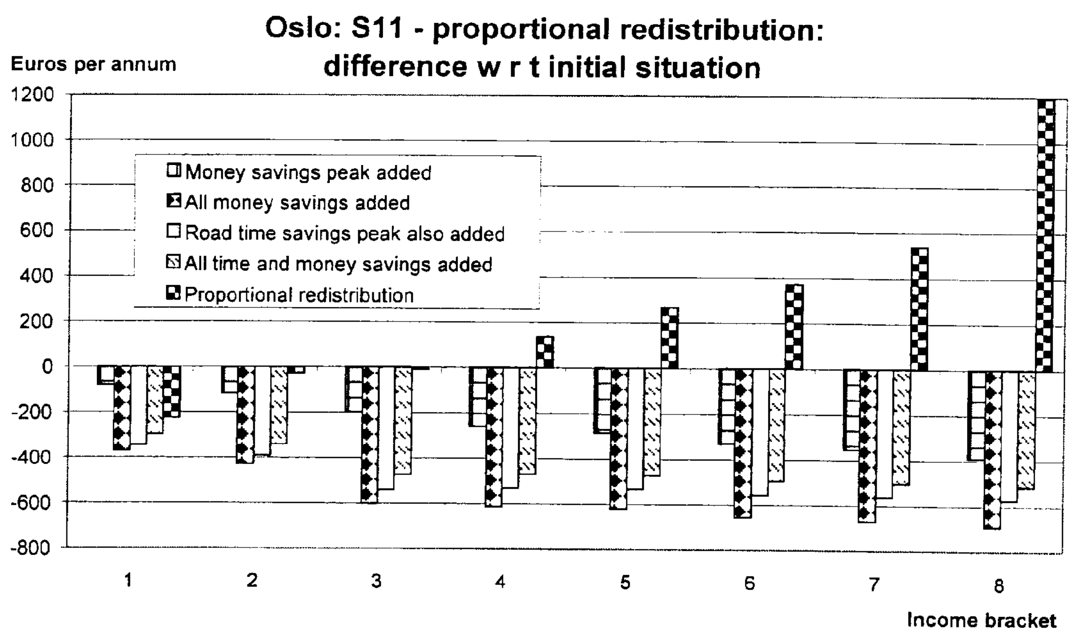

Figure 7.11. Differential effects of «first-best» marginal cost pricing by household income per consumption unit, assuming proportional recycling of revenue.

In the third column if Figure 7.11 («Road time savings peak also added»), we compound the monetary savings of column two *and* the peak hour timesavings for motorist (item $UBE^{peak}_{r,car}$ of Table 4.3) for most income groups. As might be expected, these timesavings are generally larger among the more affluent.

In the fourth column («All time and money savings added»), the entire consumer surplus change is included. By and large, the upper income brackets are seen to incur a larger welfare loss (prior to revenue recycling) due to first-best marginal cost pricing than do the lower income groups, at least in terms of absolute willingness-to-pay.

Note, however, that our analyses do not take account of differences in the marginal utility of money. Since the marginal utility of money is generally higher among the less affluent, it may be argued that our efficiency and equity analyses, based as they are on a willingness-to-pay criterion, tend to be inherently biased against the interests of the poor – confer the recent debate between Brekke (1997, 1998), Johansson (1998) and Drèze (1998).

When the (differential) revenue and profit collected by the public treasury and operators are redistributed to the households in amounts proportional to each household's initial income, i e as a given percentage point income tax relief, the upper income brackets are seen to reap a net welfare gain, while the opposite is true of the low income groups.

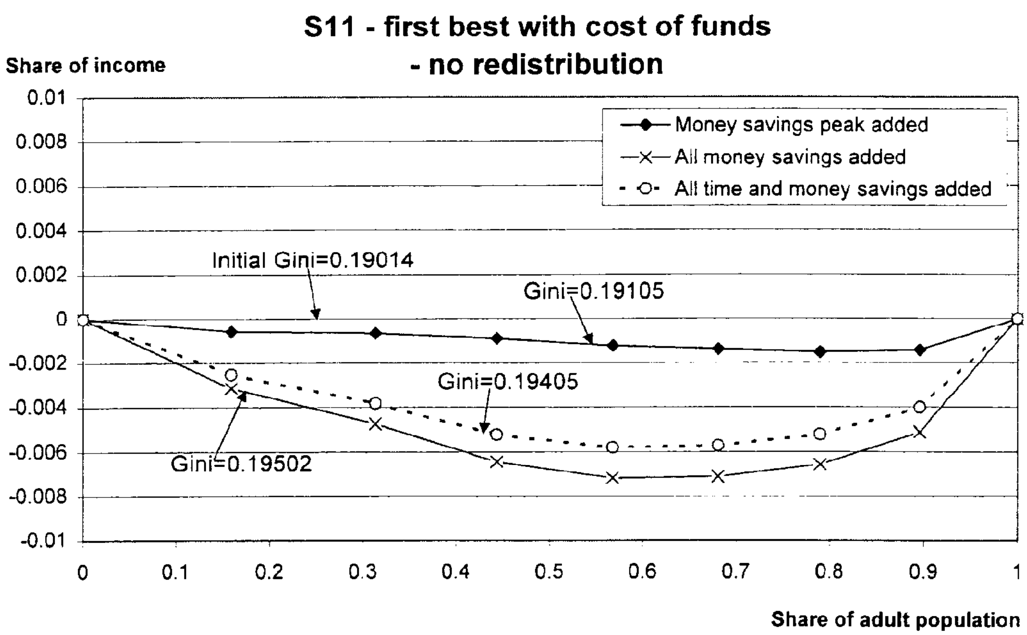

Figure 7.12. Lorenz curve differentials for the S11 scenario (first-best with cost of funds) assuming **no** or **proportional** redistribution of revenue.

These equity effects are also clearly visible in terms of Lorenz curve differentials, as shown in Figure 7.12, which is tailored to the standard introduced by Figure 6.3 above. The monetary welfare loss incurred by peak hour travellers has an only moderately adverse distributional effect, the *Gini* coefficient going from 0.19014 to 0.19105, while a much larger, adverse effect is due to off-peak travelling. The time gains, on the other hand, tend to reduce the adverse equity effect, shifting the Lorenz curve upwards compared to the situation before time benefits have been taken into account and the changing *Gini* coefficient from 0.19502 to 0.19405.

Note that, by definition, a proportional redistribution of revenue does not change the Lorenz curve or the *Gini* coefficient. Thus Figure 7.12 also represents the situation after proportional redistribution, as shown in Figure 7.11.

In Figures 7.13 and 7.14, however, we show the results of an alternative redistribution scheme, in which all individuals receive the same nominal amount of money, large enough (after tax) to exactly deplete the revenue generated by the road pricing policy. We shall refer to this redistribution scheme as a «*poll transfer*» or «*flat*» recycling.

With this kind of redistribution, all income groups receive a net welfare gain, and the lower income groups receive the largest gain, in relative as well as in absolute terms.

This is indicated by a very clear improvement in the *Gini* index, which changes from 0.19405 to 0.18574 after flat redistribution of revenue. Thus, in terms of the *Gini* index, the poll transfer leads to an improvement in the income distribution which is more than twice as large as the deterioration due to marginal cost pricing (0.19405 – 0.19014), and about 9 times larger than the effect of the monetary consumer deficit in the peak period (= 0.19105 –0.19014).

Put otherwise, it would be sufficient to redistribute only a certain share of the revenue, in order to keep all income groups at least equally well off and the income distribution at least as even as before (in terms of the *Gini* coefficient).

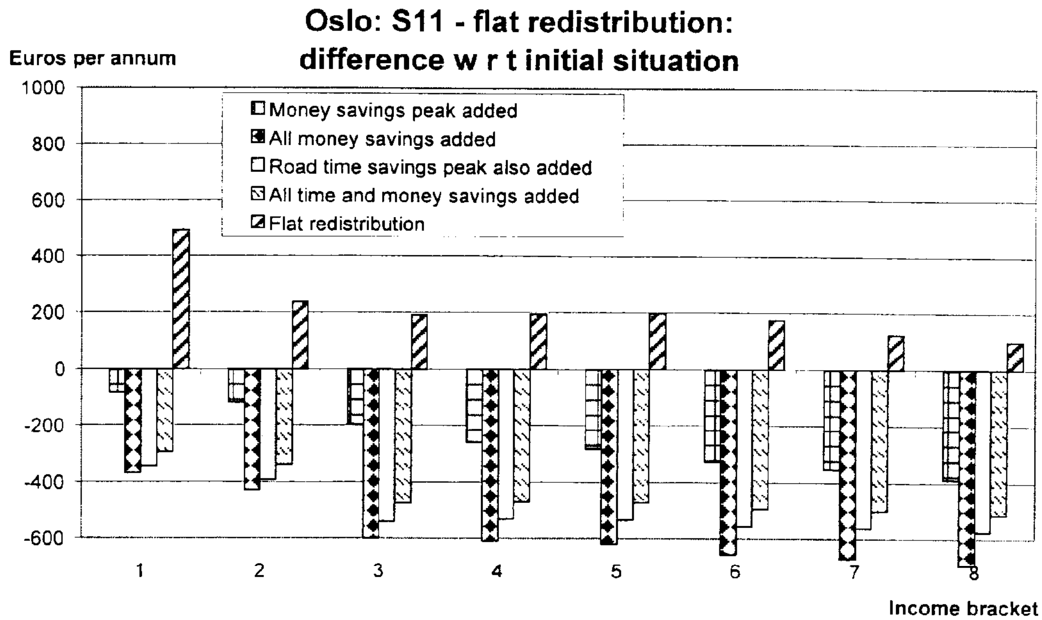

Figure 7.13. Differential effects of «first-best» marginal cost pricing by household income per consumption unit, assuming **flat** redistribution of revenue.

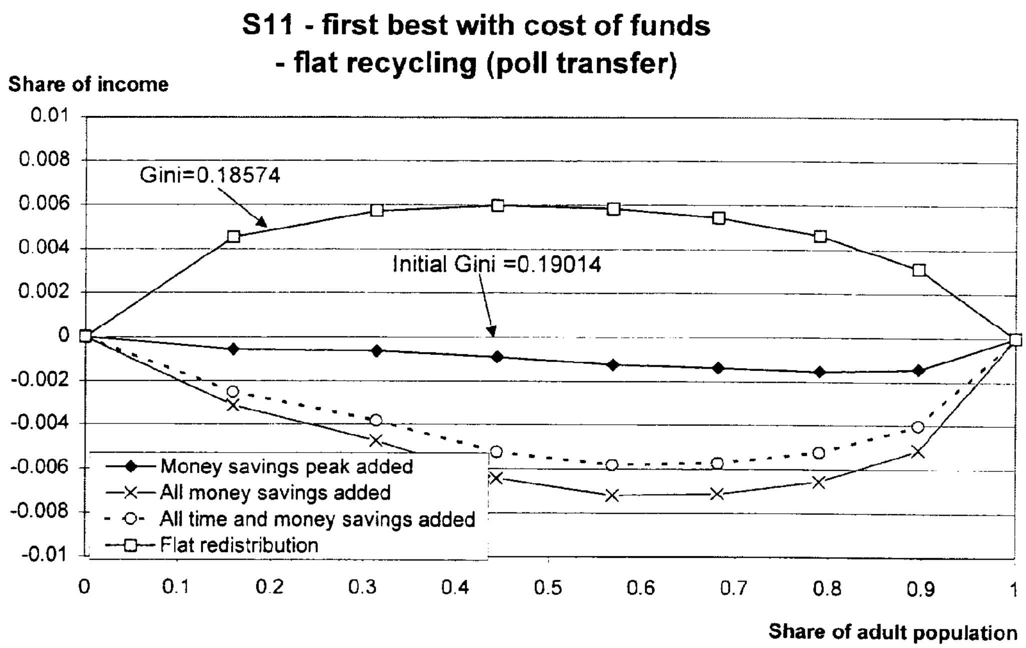

Figure 7.14. Lorenz curve differentials for the S11 scenario (suboptimal first-best) assuming **progressive** redistribution of revenue.

One might, however, question the coherence of an analysis which assumes flat revenue redistribution to the households, and at the same time includes a (non-zero) shadow value of public funds in the efficiency measure. Several interpretations are possible here.

This relates to the argument given in sections 4.2.1 and 7.3.3, on the feedback effects generated from the rest of the economy. One might say that, by *not* correcting the efficiency measure for the recycling of revenue, we include in our policy assessment a summary measure of the efficiency gains obtainable from shifting the tax burden from distortionary taxation to road user charges.

If the redistribution is done in such a way that distortionary taxation is not reduced, there is no rationale for including the shadow price of public funds in the efficiency measure. In this case, we are faced with a clear-cut trade-off between efficiency and equity: the equity can be improved through redistribution, but only at the expense of more than half the efficiency gain obtained from the *S11* marginal cost pricing strategy.

If, on the other hand, the redistribution does contribute to reduce the incidence of distortionary taxation, at a rate equal to the assumed, average shadow price of public funds, the efficiency measure has been correctly calculated and will not be altered through the redistribution. In this case, the redistribution of income will improve efficiency in other markets, the total efficiency gain throughout the economy being given – precisely – by the shadow value of the public funds being redistributed.

To the extent that the marginal tax on labour is distortionary, a redistribution scheme which lowers the *marginal* tax rate by a given number of percentage points, as in a «proportional» recycling scheme, would seem to qualify as a scheme which does not reduce overall efficiency. But this redistribution scheme does nothing to correct the income distribution.

The «flat» redistribution scheme, on the other hand, would give equal amounts to all income brackets and hence not affect the *marginal* tax rate at all. This scheme certainly improves the income distribution, but hardly the allocative efficiency of the general economy. Indeed, it is quite possible that such a scheme might even *worsen* efficiency, to the extent, e g, that the poll transfer serves to reduce the supply of labour. In such a case, the relevant shadow price of public revenue would be negative.

To ensure coherence between the assumptions made, respectively, in the efficiency calculus and in the equity analysis, we shall – in the sequel – adopt the following convention. *Proportional redistribution* schemes are linked to the scenarios assuming a non-zero shadow price of public funds, while the *poll transfer* schemes are applied only to the solutions based on a zero shadow price of funds.

The Gini coefficient of the first-best scenario *P11* with a poll transfer scheme is 0.18750, which is a reduction relative to the base case. Although overall welfare improvements are achieved, the overall welfare improvements correspond to relatively small amounts of money.

The trade-off between equity and efficiency thus seems to come back on us. It may seem that «good» (effective) redistribution schemes are bound to take something away from efficiency.

It is fair to say, however that by judging the results obtained from the RETRO model for Oslo, the equity impact of first-best marginal cost pricing is relatively modest. It could, in principle, be neutralised through the redistribution of (part of) the public revenue generated.

7.4.2 The S21/P21 scenarios (second-best under current institutions)

The equity impacts of another scenario for Oslo – the second-best scenario under current institutions (*S21/P21*) – are illustrated in Figures 7.15 through 7.18.

In Figure 7.15 we show the differential effects of second-best pricing given a 0.25 shadow price of public funds and a proportional recycling scheme. In likeness to S11 with proportional redistribution, this policy package, too, keeps the upper income groups at least equally well off, while the low-income groups lose. The changes in welfare are generally smaller than under first-best pricing (confer Figure 7.11).

On the other hand, income distribution effects are less severe (compare Figures 7.16 and 7.12). The *Gini* coefficient increases from 0.19014 to 0.19273 in the *S21* scenario – an unfavourable but rather modest income distribution effect.

A rather different picture emerges under zero cost of funds and flat redistribution. Here, the welfare improvements are very small indeed, and negative for the two uppermost income brackets (Figure 7.17). The income distribution improves, but – on account of the relatively small amounts of money which shift hands – the income distribution impact is quite small as well (Figure 7.18).

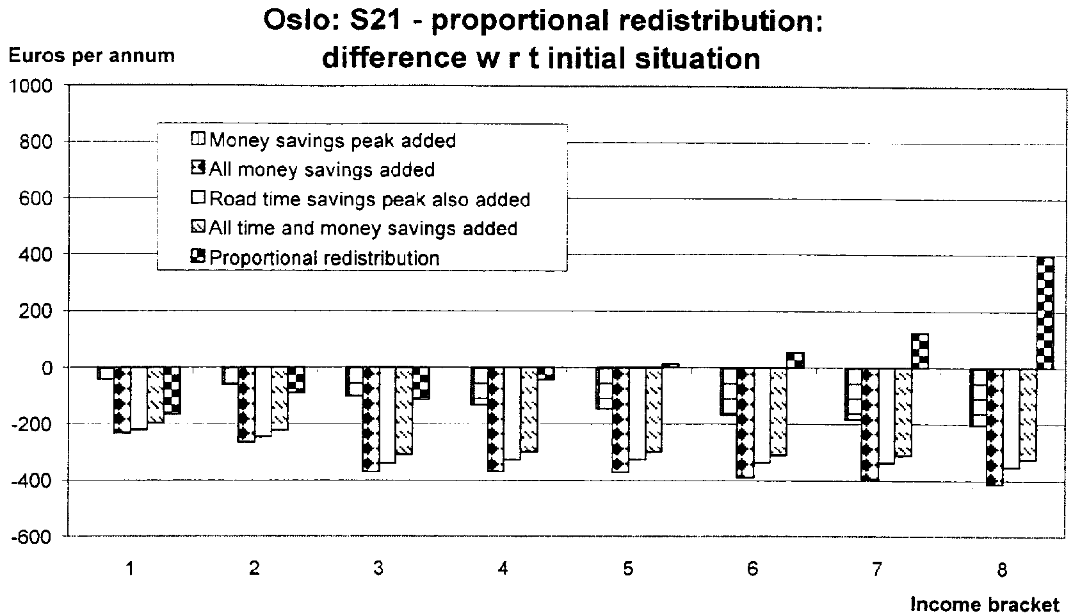

Figure 7.15. Differential effects of best practice second-best pricing under current institutions, by household income per consumption unit, assuming a **0.25** shadow price of public funds and **proportional** recycling of revenue.

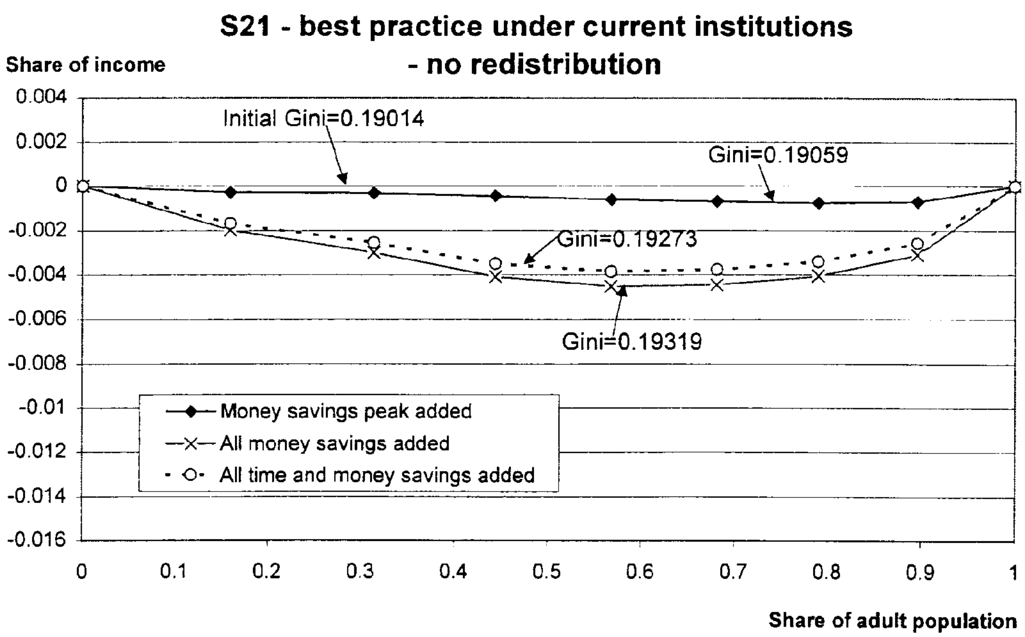

Figure 7.16. Lorenz curve differentials for the S21 scenario (second-best under current institutions), assuming a **0.25** shadow price of public funds and **no** or **proportional** redistribution of revenue.

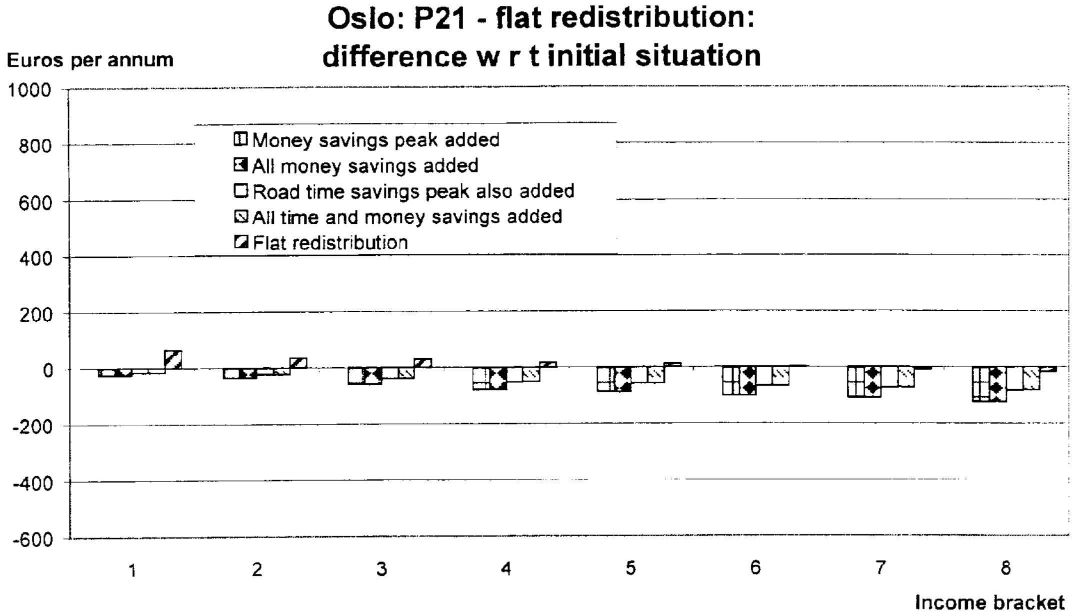

Figure 7.17. Differential effects of best practice second-best pricing under current institutions, by household income per consumption unit, assuming a **zero** shadow price of public funds and **flat** recycling of revenue.

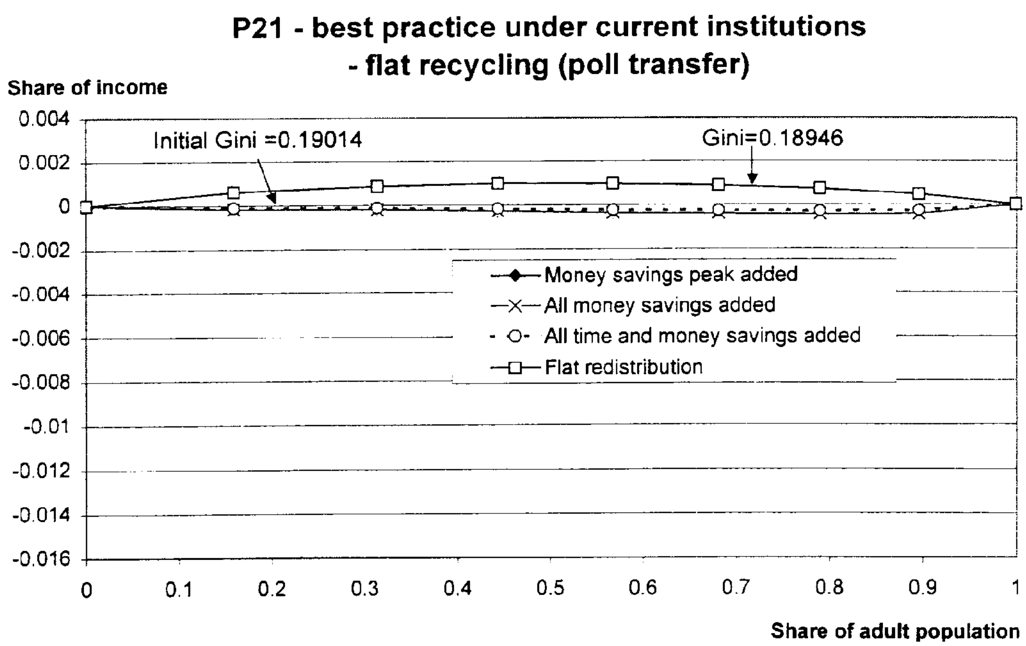

Figure 7.18. Lorenz curve differentials for the P21 scenario (second-best under current institutions), assuming a **zero** shadow price of public funds and **flat** redistribution of revenue.

7.4.3 The S22/P22 scenarios (short-term second-best after institutional reform)

In Figures 7.19 to 7.22, we exhibit similar results obtained under the *S22/P22* scenario.

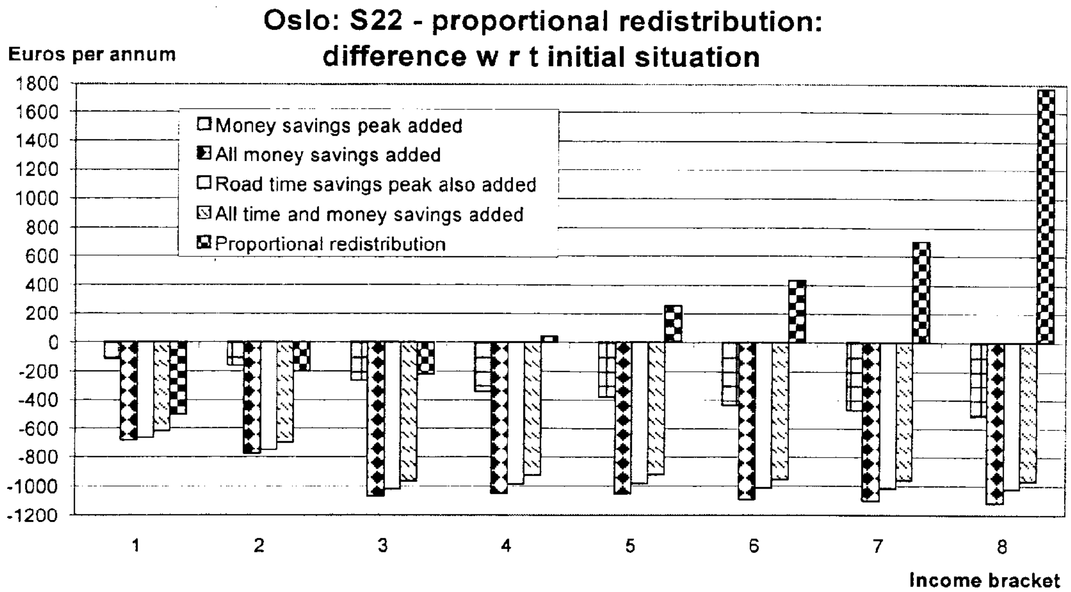

Figure 7.19. Differential effects of short-term best practice second-best pricing after institutional reform, by household income per consumption unit, assuming a **0.25** shadow price of public funds and **proportional** recycling of revenue.

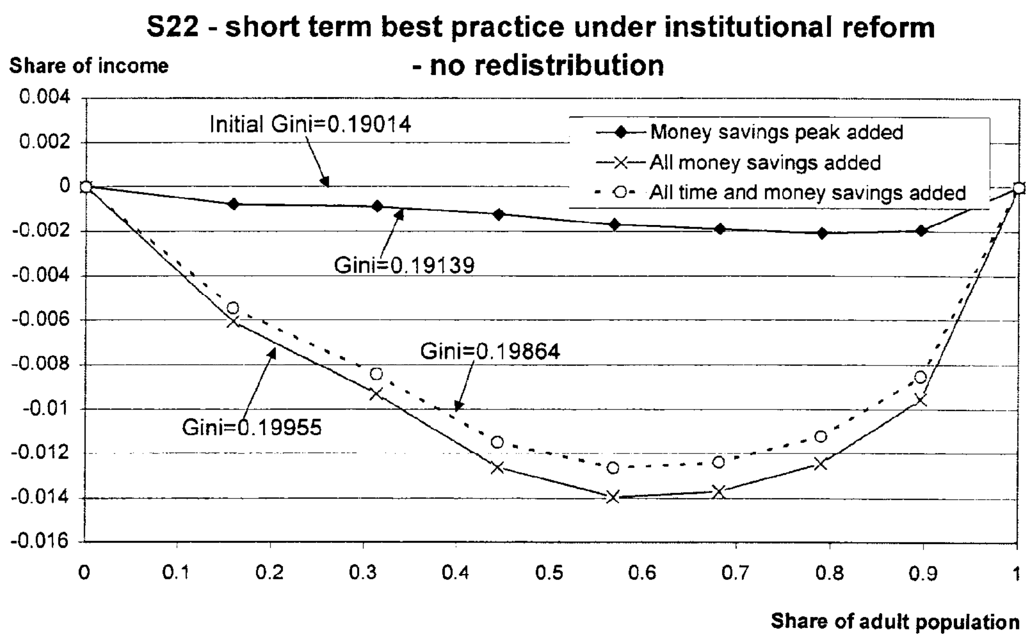

Figure 7.20: Lorenz curve differentials for the S22 scenario (short-term second-best after institutional reform), assuming a **0.25** shadow price of public funds and **no** or **proportional** redistribution of revenue.

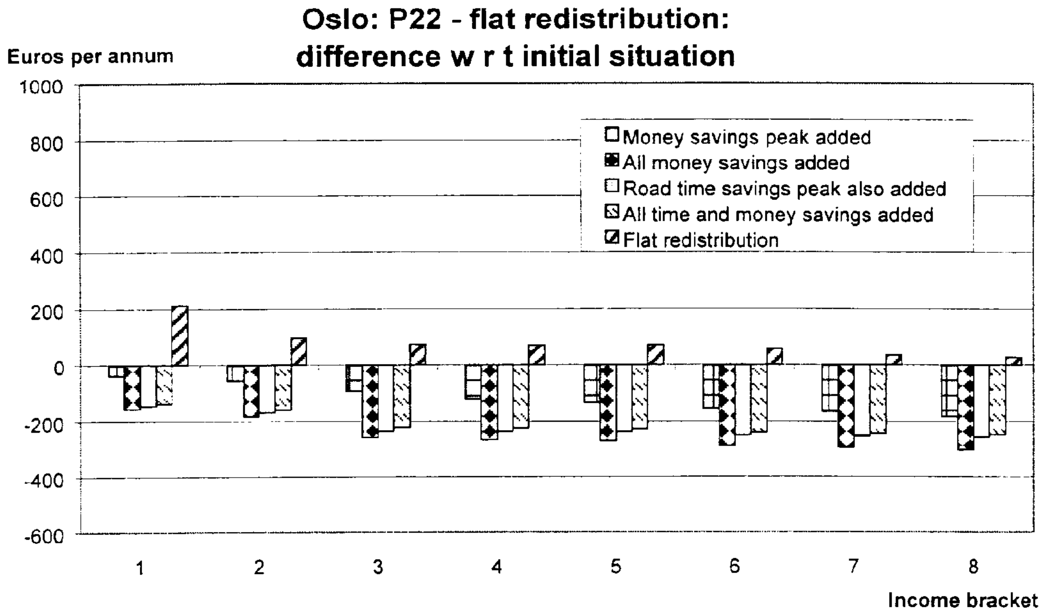

Figure 7.21. Differential effects of short-term best practice second-best after institutional reform, by household income per consumption unit, assuming a **zero** shadow price of public funds and **flat** recycling of revenue.

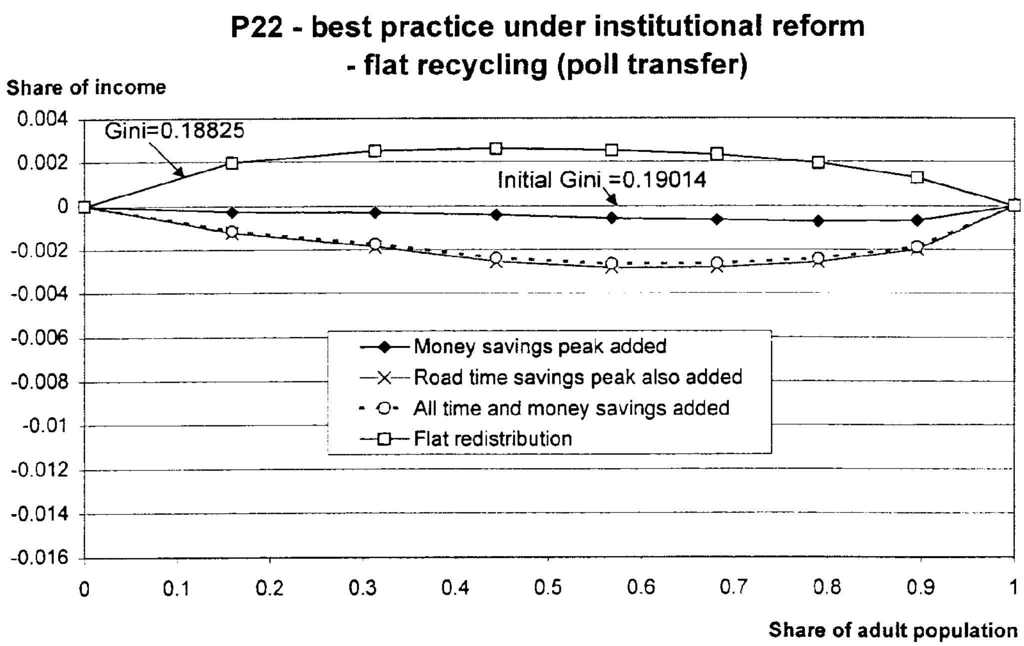

Figure 7.22. Lorenz curve differentials for the P22 scenario (short-term second-best after institutional reform), assuming a **zero** shadow price of public funds and **flat** redistribution of revenue.

Under non-zero cost of funds and proportional recycling, the large welfare gains accrue to the more affluent, while the low-income groups incur a loss (Figure 7.19). This is so because the *S22* policy generates very large revenue, which – by assumption – is recycled mainly to the higher income brackets. The equity impact is correspondingly adverse (Figure 7.20).

To an even larger extent than in the in the first-best solution, the charges levied on off-peak travel has an adverse distributional effect, bringing the *Gini* coefficient from 0.19139 to 0.19955.

If a poll transfer type of recycling is envisaged, and the shadow price of funds is consequently set to zero, much smaller, but more equitable welfare improvements are obtained (Figure 7.21). Here, all income groups obtain a small benefit after recycling, and the *Gini* coefficient improves from 0.19014 to 0.18825 (Figure 7.22).

7.4.4 The S22b/P22b scenarios (medium-term second-best after institutional reform)

The *S22b* scenario exhibits, again, considerable welfare improvements for the higher income brackets, but at the cost of adverse distributional effects (Figures 7.23 and 7.24).

Note that, in this scenario, there is an additional cash flow to be accounted for, viz the cost savings obtained by private households as they reduce aggregate car ownership (by 11.1 per cent in the *S22b* scenario and 2.8 per cent in the *P22b* case). These savings are not included in first or second column shown in Figure 7.23 (whence the label «All *variable* money savings added»). They are, however, taken account of in the fourth column («All time and money savings added»).

As noted in Section 7.3.4 above, we disregard – in this scenario – the welfare loss due to reduced availability of private cars for interregional (or longer distance) travel. On account of this, the consumer surplus gains calculated under this scenario are somewhat overstated.

The *P22b* scenario, in which no extra value is attached to public revenue and this revenue is redistributed as a poll transfer, provides small welfare gains for all income groups and a somewhat improved distribution (Figures 7.25 and 7.26).

The equity improvement is, however, smaller than in the *P22* scenario, although the overall efficiency effects are almost identical.

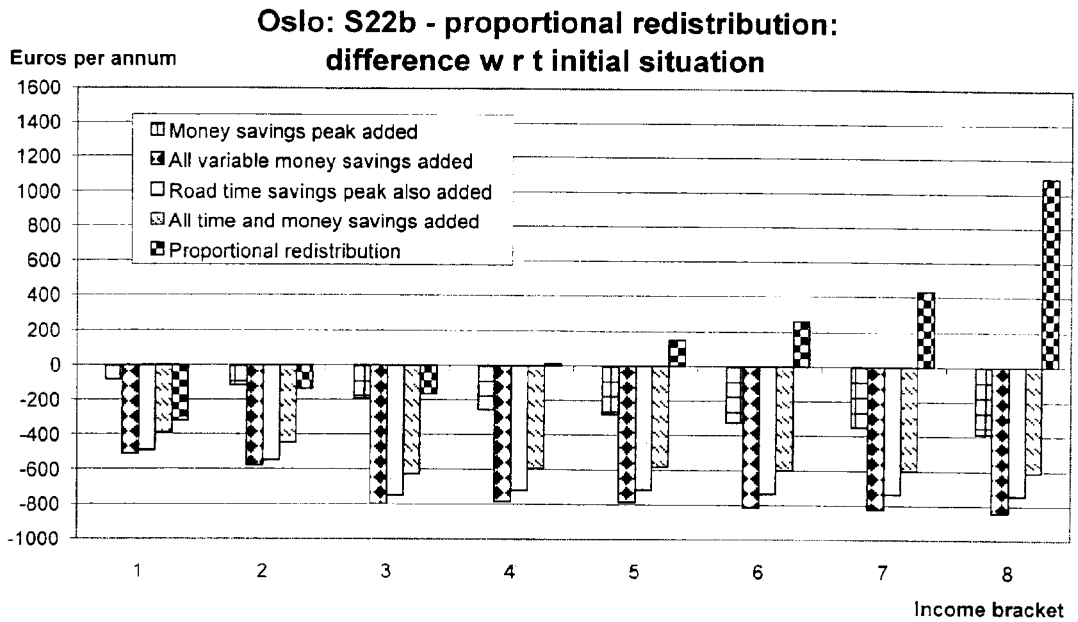

Figure 7.23. Differential effects of medium-term best practice second-best pricing after institutional reform, by household income per consumption unit, assuming a **0.25** shadow price of public funds and **proportional** recycling of revenue.

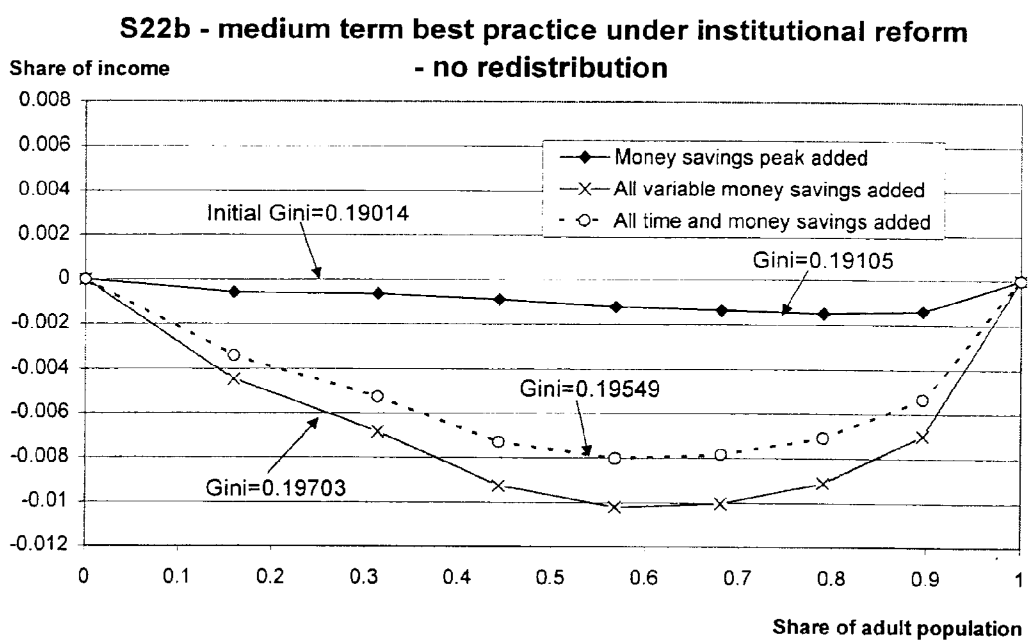

Figure 7.24. Lorenz curve differentials for the S22b scenario (medium-term second-best after institutional reform), assuming a **0.25** shadow price of public funds and **no** or **proportional** redistribution of revenue.

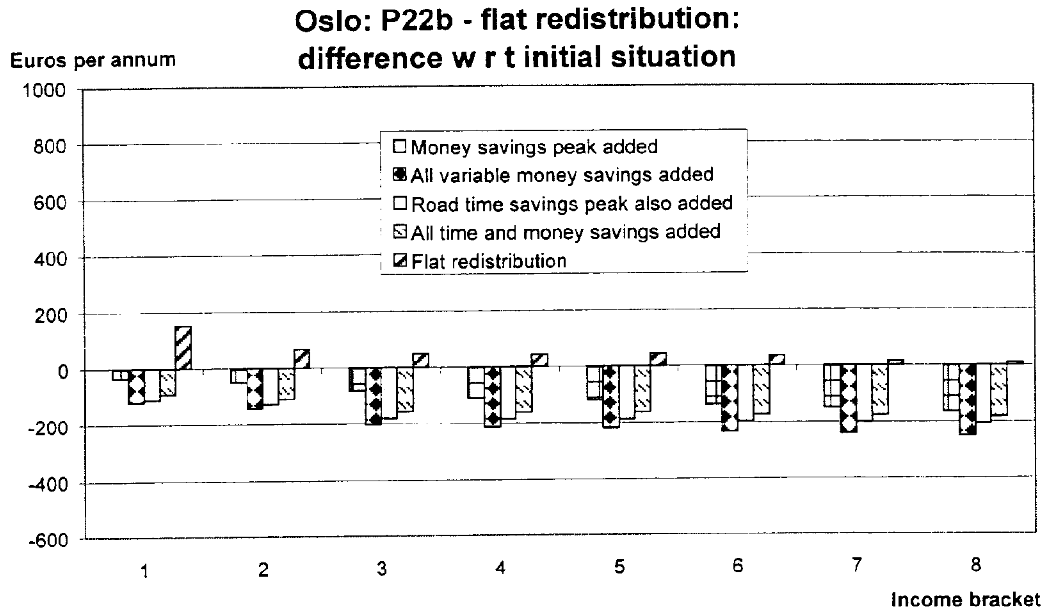

Figure 7.25. Differential effects of medium-term second-best after institutional reform, by household income per consumption unit, assuming a **zero** shadow price of public funds and **flat** recycling of revenue.

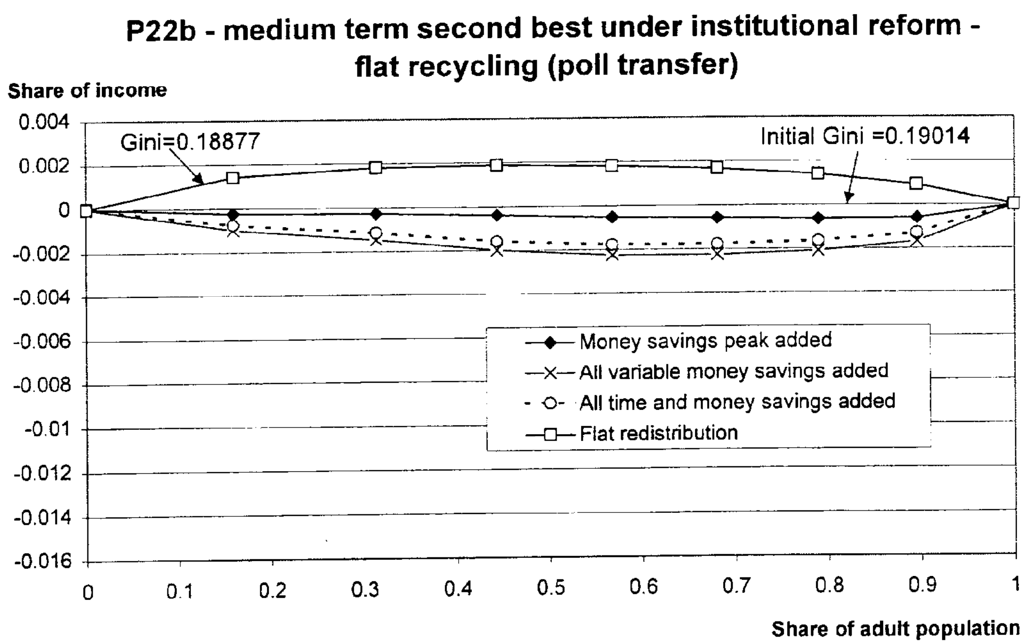

Figure 7.26. Lorenz curve differentials for the P22b scenario (medium-term second-best after institutional reform), assuming a **zero** shadow price of public funds and **flat** redistribution of revenue.

8 Summary, discussion and conclusions

The objective of this report has been to document and apply a framework for the evaluation of social efficiency of road pricing strategies and for assessing corresponding household income distribution effects in the population of the greater Oslo area.

Road pricing is defined broadly as any pricing measure to control the demand for trips on the road network. We defined marginal cost road pricing as road pricing where the values of the available transport measures are set such that the social efficiency function is maximised. We further subdivided marginal cost road pricing into first-best and second-best road pricing. Scenarios where link-based road charges are available for optimisation were classified as first-best. In the second-best scenarios we have studied, only the overall measures of a fuel tax, toll charges at the present toll ring, parking charges and a car tax were available for optimisation.

A framework for identifying first-best and second-best road pricing strategies was developed. The framework consisted of a software tool for the calculation of the social costs and benefits of new road pricing measures or changes in the level of existing measures. The welfare calculations are based on output from the transport model RETRO, which was used for the calculation of equilibrium transport quality data and travel demand. Net costs and benefits as compared to a base scenario was expressed in terms of a social efficiency function W. By repeated runs of the transport model, this function was maximised.

The base scenario represented the situation in mid 1990s, except that toll charges were set at zero. The environmental costs of noise, accidents and pollution from cars were to some extent already internalised in the fuel price of the base scenario.

For all scenarios where the shadow price of public funds was set at zero, a simplified version of the W function was maximised with respect to the road pricing measures available for optimisation. This ensured consistency in comparison between the first and second-best scenarios in so far as benefits and costs were calculated for the same markets in both. However, in the second-best optimisations, it would have been possible to take account of the public transport consumer and producer surpluses in the optimisation and evaluation, thus making these solutions the second-best solutions in a broader setting than the one defined for first-best optimisation.

Although some minor simplifications of W was needed in order to obtain the first-best solution with a shadow price of public funds of 0.25, the full W was used for evaluation of all scenarios with a shadow price of public funds of 0.25.

The equity aspects of road pricing have been analysed. The equity analysis was based on different assumptions regarding how government revenue is redistributed back to the households. There is a close link between the redistribution scheme and the shadow price of public funds. In scenarios with a shadow price of public funds of zero, taxes on household income were reduced by equal absolute amounts for all subgroups, whereas in scenarios with a shadow price of 0.25 tax-rates were reduced by the same percentage points for all.

A set of scenarios was constructed. A subset of the scenarios shows the short-term effects of road pricing, whereas the other subset shows the long-term effects. Our first-best scenarios take account of short-term effects only. Although we did not investigate first-best solutions taking account of medium-term effects, this could possibly be done by in an iterative procedure, involving the car ownership model when optimising with respect to certain measures that affect car ownership for a given set of link-based charges, then using this environment when optimising with respect to the link based charges.

8.1 Efficiency

The first-best scenario P11 and the second-best scenarios P21 and P22, with a shadow price of public funds of zero, are all based on the simplified *W*. As car ownership was assumed to be unaffected (i.e. equal to the car ownership in the base case), these scenarios are considered short-term. Peak and off-peak toll and parking charges were available for optimisation in both P21 and P22. In addition, the fuel tax was available in P22. The total efficiency gain in the scenarios was 75, 12 and 17 Euros per capita per annum, respectively (Figure 7.1). This shows that there is a gap between the link-based first-best road pricing and the more feasible second-best.

The scenarios S11, S21 and S22 corresponds to P11, P21 and P22, except that the shadow price was set at 0.25 and the full *W* was used for evaluation. The total efficiency gain in S11, S21 and S22 was 199, 56, 157. Generally, the efficiency gain is larger. The reason is that in scenarios with a 0.25 shadow price of public funds, the use of the measures to reduce congestion problems is strengthened and amplified, as the fiscal gains are more important. This leads to larger money transfers from car drivers to the government. But the gap between the efficiency gain of the first-best and second-best scenarios is smaller than for scenarios with a shadow price of public funds of zero. This is due to the fact that the fiscal gains are fairly independent of whether road pricing is link-based or less closely related to the particular levels of congestion on each link.

For all scenarios, the money transfers from travellers to the government are larger than the reduction in congestion costs.

With the very imperfect road pricing schemes that can be constructed on the basis of the present toll ring, an additional distance-based instrument like the fuel tax is useful. Thus the overall welfare gains of 12 in P21 and 56 in S21 are raised to 17 in P22 and 157 in S22 (Figure 7.1). However, these gains occur at the expense of travellers, who will cut their losses by selling off cars. But even when they are allowed to do so – in P22b and S22b – the welfare gain stays at 17 in P22b, while falling off to 110 in S22b.

In addition to improving the welfare gains, the introduction of the fuel tax as an instrument to be optimised makes the optimal toll charges somewhat more acceptable (Table 7.3). Thus if a somewhat higher level of the fuel tax can be defended at the national level, it might in fact be easier to implement optimal toll charges at the local level. These ties between the optimal tolls and the fuel tax has been ignored in the public discussion on road pricing and fuel taxes in Norway. On the other hand, there is more to be gained by extending the system of toll stations and make it more similar to perfect link-based road pricing, than to supplement the present toll ring with distance-based measures. This is especially true for the zero shadow price scenarios, where there is a 50% improvement in welfare when going from P21 to P22b, but a potential for a 625% gain when going from the present toll ring to perfect link-based charges. Paradoxically, to implement road pricing at a system of rings or by relocating the present toll ring is very seldom mentioned as an option in the public discussion on road pricing.

The only difference between scenarios P22b and S22b and P22c and S22c is that in the last two, an annualised car tax is added as a measure available for optimisation. Including such taxes seems to have radical effects. Whereas the social efficiency gain of P22b and S22b are 17 and 110 Euros per capita per annum, the social efficiency of P22c and S22c are 293 and 456 Euros (Tables AII.9 and AII.10 in the Appendix, respectively). The optimal car tax is 5.3 and 4.3 times the tax in the base case, producing huge money transfers from travellers to the government.

It is worth mentioning again that the benefits of car ownership are nor very well accounted for (see section 4.2.5). In addition, the effects in the "c" scenarios are far too large to be predicted reliably by the transport model. This is why these scenarios are ignored in Figure 7.1.

P22b, S22b, P22c and S22c are optimised with respect to the medium-term effects of both regional and national measures. The medium-term effects were connected to car ownership. Further research should reconsider cost-benefit analysis of the medium-run effects and take land-use changes into account in order to capture the long run effects.

8.2 Equity

To investigate the effects of the different road pricing scenarios on equity, the prototypical sample representing the population was subdivided in eight income brackets in terms of household income per consumption unit, where each bracket covers approximately one eight of the adult population. To quantify the change in the economic situation as a consequence of road pricing for different household subgroups, we calculated the differential effects on “partial generalised income”.

As mentioned in the previous section, in all scenarios road pricing produces large money transfers from car drivers to the government. There is a close interrelationship between the scheme for redistribution to the population subgroups and the shadow price of public funds. If the redistribution is performed in such a way that distortionary taxation is not reduced, there is no rationale for including the shadow value of public funds in the efficiency measure. Thus we are faced with a clear-cut trade-off between efficiency and equity: equity can be improved through redistribution, but only at the expense of certain parts of the efficiency gain.

If, on the other hand, the redistribution does contribute to reduce the incidence of distortionary taxation, at a rate equal to the assumed average shadow price of public funds, the efficiency gain has been correctly assessed and will not be altered through the redistribution. In this case, the redistribution of income will improve efficiency in other markets, the total efficiency gain throughout the economy being given – precisely – by the shadow value of the public funds being redistributed.

Social efficiency was maximised for scenarios with a zero shadow price of public funds and, in other scenarios, 0.25. The zero shadow price of public funds is consistent with the assumption of flat redistribution (i.e. equal absolute amounts of money to all households consumption units). Scenarios with a shadow price of public funds of 0.25 were implicitly based on the assumption of a proportional redistribution (i.e. that the income tax-rate was reduced by the same percentage for all households) or no redistribution.

In the case of no redistribution, all income groups suffer a welfare loss as measured by the change in consumer surplus. The monetary welfare loss incurred in the peak period was larger in the higher income brackets, whereas the welfare loss was much more evenly distributed between income groups in the off-peak period. By and large, the upper income brackets suffered larger welfare losses (prior to revenue recycling) from first-best marginal cost pricing than the lower income groups, at least in absolute terms.

Although we have linked the level of the shadow price of public funds to specific schemes of redistribution, for comparative reasons we investigated the equity effects of the S11 scenario for all redistibution schemes – no redistribution, flat redistribution and proportional redistribution.

Based on the Gini coefficient we concluded that "no redistribution" results in an adverse equity effect. Exactly the same adverse equity effect remains after proportional redistribution (i.e. a net welfare gain for the upper income groups, while the opposite is true for the low-income groups). With flat redistribution, all income groups receive a net welfare gain, and the lower income groups receive the largest gain. The welfare gain was largest for the low-income groups, both in relative as well as in absolute terms. The reason for the larger absolute gain for the low-income groups is that these groups loose less in absolute terms prior to redistribution. Hence, as each household receives the same nominal amount of money, the net absolute welfare gain becomes higher for the low-income groups. This is indicated by a very clear improvement in the Gini coefficient. Thus, in terms of the Gini coefficient, the flat redistribution improves household income equity.

For the P21 and S21 scenarios we used the flat and proportional redistribution schemes to investigate the effects on equity. In the S21 scenario with proportional redistribution, the upper income groups are at least equally well off, while the low-income groups loose. The changes in welfare are generally smaller than under first-best pricing. On the other hand, the income distribution effects are less severe. For P21 with flat redistribution, the income distribution improves but only by a small amount.

Similar analyses were made for the P22, S22, P22b and S22b scenarios, and results similar to those for the P21 and S21 scenarios were obtained.

The efficiency and equity results are summarised in Table 8.1.

Table 8.1. Social efficiency gains and equity effects for first-best and second-best scenarios. In base-case, the social efficiency gain is zero and the Gini coefficient is 0.19014.

Scenario	**Net social gain (Euro per capita per year)**	**Compensation/Gini coefficient**
P11	75	3264 NOK/0.18750
S11	199	4.4 %/0.19405
P21	12	645 NOK/0.18946
S21	56	1.73%/0.19273
P22	17	2000/0.18825
S22	157	6.5%/0.19864
P22b	17	1972 NOK/0.18877
S22b	110	4.1%/0.19549

8.3 Conclusions

The following main conclusions were drawn from our study of first-best and second-best road pricing strategies for Oslo and Akershus:

- Marginal cost road pricing based on available instruments (including the present location of the toll ring) can produce significant or even substantial economic benefits.
- The benefits do to a large extent depend on the value of the shadow price of public funds, which again depends on whether taxpayers' money is a particularly valuable resource, and whether transport taxes have less distortionary effects than other taxes. If this is the case in the Oslo region, then road pricing is above all an efficient form of taxation. Therefore, the actual distortionary effects of transport taxes merit future study.
- Road pricing does also produce significant environmental benefits.

- In the conditions prevailing in the Oslo region, travellers' time gains are always less than their monetary loss. Consequently, travellers as a group stand to lose by road pricing unless the revenue in one way or another is distributed back to them (e.g. in the form of income tax cuts, lump-sum payments or the provision of a public good for which there is sufficient willingness-to-pay).
- The revenue is usually high enough to allow full compensation to travellers. Road pricing, when coupled to such a recycling scheme, could then be a Pareto improvement. (This statement is subject to the qualification that the effects of the redistributed income on travel decisions have not been studied).
- Prior to redistribution, road pricing has slightly unfavourable equity effects, as the costs borne by low-income groups will be a proportionally higher share of their household income.
- If, however, the revenue is redistributed to the households in a way that gives approximately the same amount of money to every household, then the negative distributional effects will be reversed, and a more equal income distribution is achieved.
- According to our calculations, road pricing does not lead to a greater loss of mobility in the low income groups than in the other groups – rather the opposite. There are no indications that the poor travellers are priced off, while the rich pay their way. This can probably be explained by the fact that the high-income groups have a higher travel frequency, especially by car in rush hours, and are therefore harder hit by high peak toll charges.
- Road pricing entails a sharp conflict between efficiency and equity objectives. If the revenue is redistributed so as to improve the income distribution, road pricing will not contribute to improve the efficiency of the tax system. Thus there will be no "double dividend". If, on the other hand, the revenue is used to cut marginal taxes on labour, or used to produce a public good for which there is a high willingness-to-pay, there *will* be a double dividend. But in that case, the initial inequality brought about by road pricing is not counteracted.
- Marginal cost road pricing will lead to a significant mode shift from car to public transport in the high-income groups. Even walking and cycling is expected to increase significantly. The health effects of this, consisting of the benefits of physical activity and improved air, and the costs of more accidents, merit future study.
- Assuming a shadow price of public funds of 0,25, the optimal toll charge in rush hours becomes approximately 4.0 Euro (4.2 times the current level of 0.95 Euro) in Oslo. The optimal toll charge in the off-peak period becomes 2.7 times the current level.
- These charges generate a revenue capable of reducing the municipal income tax in Oslo and Akershus by 1,7 percent units, or to allow a lump-sum transfer to each household of approximately 290 Euros per year.

- Assuming a zero shadow price of public funds, the optimal toll charge in the rush hours becomes about 2,7 times the current level, whereas crossing in off-peak periods should be free. In this case, the revenue is significantly lower, corresponding to 0,3 percent of gross income or 57 Euros per household per year.
- Assuming that the fuel tax could be used as a local instrument, the optimal fuel tax in Oslo and Akershus under the assumption of a shadow price of public funds of 0.25 would be twice the current level. In this case, there are less need for high toll charges: 3.5 times the current level in rush hours and 2.3 times the current level in off-peak periods.
- This policy would generate a revenue sufficient to reduce the income tax by 4 percent of gross income, or to give to each household in Oslo and Akershus a sum of 679 Euros per year.
- Although these effects are substantial, only a fraction of the theoretically achievable welfare effects are reaped by marginal cost road pricing at the present toll ring. There is a case for considering slightly more advanced forms of road pricing, including a more favourable location of the ring or a system of several rings.

8.4 Comparison with previous studies of marginal cost road pricing in Oslo

Road pricing in the case of Oslo has been investigated in several previous studies. Larsen and Ramjerdi (1990) used a joint mode choice and assignment model of the Oslo region with 461 zones. They calculated toll fees for an alternative "optimal" location of the Oslo toll ring. Their calculations suggest that, for the case of the present location of the toll ring, inbound traffic should be charged a toll of NOK 25 during the peak periods and zero during other periods. This result is very similar to our result for the P21 scenario, where the optimal toll charges in peak and off-peak were NOK 21.6 and zero, respectively.

Ramjerdi (1995) develops a framework for the incorporation of the shadow price of public funds in the evaluation of road projects that are financed through road pricing. She then applies this framework to the evaluation of alternative road pricing schemes for Oslo. The distinctive feature of her work is that she derives the marginal welfare loss of raising funds through a particular road pricing or cordon toll scheme by calculations that can be performed on transport model output. She is then able to compare it to the shadow price of raising funds through general taxation. If the latter is the greater number, road expansion should be financed through road pricing. We may assume that the higher the required funding, the greater will be the welfare loss of raising even more money through road pricing. Eventually, it may pay to use general taxation for the rest of the required funds.

Given that a prioritised list of road investment projects exist, this work may point a way to constructing algoritms for the optimisation of strategies consisting of both investment and pricing instruments. Take on one more investment project, then compute the shadow prices to see if it should be financed by tolls or general taxation, etc. However, as investment is not included in our pricing strategies, we have not made use of this possibility.

It must be pointed out that Ramjerdi's partial equilibrium shadow price of raising funds through transport taxes does not take account of distortionary effects of transport taxes outside the transport sector. There is still a need to address this issue. If there were no mispricing of the goods and services that need transport to be produced or performed at the destinations, all welfare effects of transport policies could be correctly evaluated in the transport markets alone (Martinez 1995, SACTRA 1999, Venables and Glasiorek 1999). In that case, Ramjerdi's concept of transport sector specific shadow prices of public funds would be sufficient for evaluation of transport infrastructure and pricing strategies. Generally, this is not the case.

In the case study, Ramjerdi used EMME/2 for implementation of a transport model with simultaneous mode choice and equilibrium assignment, and applied her framework to the evaluation of the different road pricing schemes. The generalised car link costs include time costs and toll costs, but variable car costs are not included in the link costs. Simulations are performed for peak periods, "between peak" periods and "other". The pricing schemes are (1) the present road pricing scheme for Oslo, (2) the "optimal" toll ring scheme from Larsen and Ramjerdi (1990) and (3) a "socially optimal" road pricing scheme. For the socially optimal road pricing scheme, the average toll fees for different trip distances in the peak period (one way trip) vary from zero to NOK 8.42. This is similar to the average toll fee of NOK 12 and NOK 20 (two-way trips) in the P11 and S11 scenarios, respectively. Ramjerdi (1990) also use the framework to evaluate the part of the "Oslopakke 1" investment package. The package is evaluated for (a) no tolling scheme and (b) the "optimal" scheme as given by Larsen and Ramjerdi (1990). In the latter, a toll of NOK 20 collected on inbound traffic during the peak periods approximates the marginal cost of travel. This is lower than the "optimal" fee of NOK 25 with the present road network.

Larsen and Rekdal (1996) study whether toll rates, differentiated by time of day at the toll cordon in Oslo, is a cost efficient way to reduce air pollution from road traffic in the central area of the city. In their analysis they use an EMME/2-based transport model for the Oslo-region. In the model, peak travellers can choose between three different hours with respect to when to make their car trip. Public transport is also available as an option. A logit model that includes cost and time of travel determines the choice between the four alternatives. Within the ranges studied, they assume that the demand for commercial traffic is unaffected by the variation in the toll rates and travel times. Also, a certain fraction of the travellers are assumed to be captive to public transport. Time values for passenger transport, business and freight were set at NOK 36, NOK 60 and NOK108, respectively. They use their model to simulate 4 strategies. The first includes differentiated rates on the present toll cordon. The toll rate is increased from the present average of NOK 8 for light vehicles to NOK 30 in the two hours with maximum traffic (one hour in the morning and one in the afternoon). For the hours before and after the maximum hours a toll rate of NOK 15 is assumed. For the mid day working hours the toll rates are assumed to remain at present levels, while the toll is zero between 6 PM and 6 AM on workdays and in the weekends. The toll for heavy vehicles is assumed to be twice the rate for light vehicles (as today).

In the second scenario, the tolling system is changed, in the third scenario the public transport frequency is increased by 25 % in peak periods, and in the fourth scenario both the tolling system and the public transport frequency are changed. In addition to changes in transport behaviour, Larsen and Rekdal also report some economic consequences. The results include (1) The reduction in petrol consumption for traffic on and inside Ring Road 2 in the maximum peak hours, (2) The annual value of time savings and operating cost savings for the road traffic remaining in the system, (3) Changes in annual revenue from the toll system, (4) Changes in annual fare revenue for the public transport system and (5) The value of travel time savings for public transit riders.

Based on model calculations they find that the average marginal costs of one extra roundtrip in the peak hours with the present toll charges amounts to around NOK 45. They point out that the average marginal costs will decrease with higher toll charges and estimate that a one-way toll charge in the peak hour of NOK 30 will internalise the external cost of one extra car trip. They did not derive this estimate by optimisation. However, as the average congestion cost is higher in the most congested peak hour than in the whole of the peak period, their estimate conforms reasonably well to our results from the P21 scenario, where the optimal toll charge in the whole peak period is NOK 21.6.

Grue et al. (1997) describe principles for calculation of congestion costs and congestion pricing, and report results from case studies in Oslo and Trondheim. An EMME/2 representation of the network in Oslo and Akershus in the mid-1990s was used as a basic model for Oslo and Akershus. Calculations with the model show that the average marginal congestion costs of a round trip by car in the peak hours is NOK 42. They do also calculate the average marginal costs for round trips between specified pairs of zones. For trips from suburban areas to the city center in the morning peak hour, 0700-0800, the average marginal cost is NOK 25. For longer trips to the city center the average marginal cost is NOK 50. However, their model does not include mode choice, destination choice and trip frequency.

They define (a) a reference scenario, (b) a scenario with the present toll ring and toll charges, (c) time differentiated toll charges at the present toll ring and (d) first-best congestion cost pricing. They use the transport model and a simple cost-benefit analysis (with zero shadow prices of public funds) to evaluate the scenarios in terms of net annual social benefits relative to the reference scenario. For Oslo and Akershus, the reference scenario is similar to the base scenario that is used in this report (with zero toll charge). Their scenario (d) is similar to P11.

According to their calculations, annual per capita social benefits of scenario (d) amounts to NOK 380 per year, whereas the social benefit of P11 is NOK 593. The figures are in the same order of magnitude, and the difference can be explained by the fact that the transport models used by Grue et al is somewhat different from ours and the cost-benefit analysis is somewhat simpler. Based on the calculated average marginal costs of today and the assumed reductions if congestion cost pricing is introduced, Grue et al. (1997) consider NOK 30-50 to be a reasonable charge for commuter round trips by car to the city center, consisting of a trip in the morning peak hour and a trip back in the afternoon peak hour. They also discuss the equity aspects of road pricing, pointing out that the equity effects of road pricing depend on the fact that some people need a car more than others, income differences, and residential locations. Based on empirical data from the1990 travel survey, they analyse (1) the share of trips that are work trips, (2) the pattern of residential location for families and locations of the kindergartens that they use, (3) the residential location and work place and corresponding average marginal congestion costs on the trips to work, and (4) the relationship between income and the number of trips by car in the peak hours. The empirical results give some idea of how different groups are affected by a specific road pricing scheme. However, they do not compute overall measures of income inequality.

Larsen (1997) discusses cost efficient peak traffic in relation to the provision of road capacity, congestion pricing and public transport supply. The approach is highly stylised. Optimal road tolls are calculated for a corridor with two modes. The corridor consists of a 15-km road used for commuting towards the city centre. The demand model he uses is an aggregate logit model of mode choice (car driver and public transport) for trips to one (unspecified) destination in the city centre. Although parameters are set to reflect typical Oslo values, this study is a conceptual and illustrative analysis rather than a comprehensive real-world model exercise. The optimum transport policy is determined by maximising an economic efficiency function (travellers surplus + public transport revenue – public transport cost) with respect to congestion pricing and fares under different assumptions about road capacity, public transport speed, the elasticity of demand and the shadow price of public funds. Logsums are used as a measure of traveller's benefits. The mathematical problem he solves can be formulated as non-linear optimisation with non-linear constraints. Furthermore, the optimal transport policies are derived with and without congestion pricing, different road capacities, and with and without a bus lane.

Larsen's alternatives with and without a shadow price of public funds, but including congestion pricing and public transport that does not interfere with private cars, bear some resemblance to our P21 and S21 scenarios. His alternatives with a zero shadow price have alternative road capacities and speeds for public transport. The optimal road tolls for the alternatives are 27.40 (1600 cars/h and 40km/h), 22.90 (2000 cars/h and 40km/h), 25.70 (1600 cars/h and 50km/h) and 21.30 (2000 cars/h and 50km/h). For round trips, a corresponding charge for the trips out of the city centre must be added. If we assume that the charge in and out of the city are the same, then congestion charges for round trips of this type are approximately NOK 50. This is considerably higher than in P21 where the one-way toll charge is NOK 21.6. Also, it is higher than NOK 30 as suggested by Larsen and Rekdal (1996) but within the range of NOK 30-50 as suggested by Grue et al. (1997). Corresponding results from alternatives where the shadow price of public funds were 0.25 are 35.9, 32.2, 35.2 and 31.7, for trips towards the city centre, whereas the optimal toll charge in S21 was 34.2 for a round trip.

In these studies, the methods that have been used to determine the optimal charges differ, as do the assumptions about time values etc. Some of the previous estimates are partly based on subjective judgement. Larsen and Rekdal (1996) and Grue et al (1997) are similar in many respects. The transport model that is used consists of mode choice, choice of time of day and assignment. Four time periods are considered. Inside one of them, the peak period trips can be transferred between hours. The link costs are generalised costs, including speed-dependent car costs. The setting in these studies is broader than in the previous ones, as consequences for public transport are also evaluated. Except for an estimation of ideal first-best link-based charges in Grue et al, there are however no attempts to find optimal charges, as only a few alternative sets of charges are considered.

The present report uses a broader setting than the previous studies and a more advanced method of optimisation to determine marginal cost road charges. Also, we quantify the equity effects, which was not done in any of the previous studies of marginal cost pricing in Oslo.

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Appendices

Appendix I

Maximisation of social efficiency

Cost-benefit analysis can be used to evaluate the economic implications of an alternative scenario relative to a base scenario. Social efficiency can be expressed as a function $f(\mathbf{p})$:R_m -> R with respect to a vector of n policy measures $\mathbf{p} = [p_1, \ldots, p_m]$.

A non-linear optimisation algorithm is needed in order to obtain a solution to the maximisation problem,

$$\max_{\mathbf{p} \in R_m} f(\mathbf{p})$$

Non-linear optimisation algorithms are based on different principles. An important difference is that some algorithms require the derivative, $df / d\mathbf{p}$, whereas so-called DUD algorithms (Dosn't Use Derivatives) does not. In general the former have higher order rates of convergence, whereas the latter are more robust and easy to apply.

Optimization algorithms

The choice of an optimisation algorithm for the maximisation of a given objective function depends on certain qualities of the objective function.

Some optimisation algorithms require the value of the derivative of the objective function for arbitrary values of function arguments. The derivatives of simple functions can often be expressed as analytical functions.

For other functions, finite differences can be used to approximate the derivatives. Although algorithms that use values of the derivative are often efficient in terms of function evaluations, it is sometimes cumbersome to establish the routine that calculates the values of the derivatives.

Some optimisation algorithms apply one-dimensional minimisation along lines in multidimensional space. Powell's Method (Press et al, 1988) is of this type. It uses information about the optima obtained from previous line maximisation in the multidimensional space in order to choose new directions for line maximisation.

A line maximisation algorithm performs the line maximisation. Hence, to apply optimisation algorithms of this type, it is necessary to set two convergence criteria

- one for line maximisation and one for the overall multidimensional function maximisation.

Application of the Simplex algorithm requires the specification of only a single convergence criterion. Evaluation of the derivative of the objective function is not needed. Besides this, the method is easily understood and implemented. However, it is not very efficient in terms of the number of function evaluations it requires.

Values of the derivative of $f(\mathbf{p})$ are not easily available. Moreover, it is not easy to pre-set the convergence criterion. Due to the long computing time, it is more desirable to monitor the change of function and parameter values and terminate the optimisation algorithm when changes are considered small. Considering the long computing time, this gives a flexible compromе between the number of iterative runs and the accuracy of the calculated optimum.

Hence, the Simplex algorithm seems like a good starting point in the attempt to understand how to optimise the $f(\mathbf{p})$ function. Experience with the Simplex method may be of great value if more sophisticated algorithms are introduced at a later occasion.

The Simplex method is well suited for optimisation of $f(\mathbf{p})$ with and without max-min constraints on independent variables (policy measures).

Simplex method

The Downhill Simplex Method is a very robust and easy to use DUD method in Multidimensions (Nelder and Mead, 1965; Press et al. 1988). A simplex is the geometrical figure consisting, in m dimensions, of m+1 points (or vertices) and all their interconnecting line segments. In two dimensions, a simplex is a triangle, and a tetrahedron in three dimensions. Initially, the algorithm choose the vertices at m+1 points $\mathbf{P}=\{\mathbf{p}_0, \mathbf{p}_1,\ldots, \mathbf{p}_m\}$ that span R_m. The points can be given by the formula

$$\mathbf{p}_i = \mathbf{p}_0 + [0,\ldots,\lambda_i,\ldots,0], \quad i = 1,\ldots,m$$

where $\mathbf{p}_0$ is some initial guess and λ_i is a scalar. The function, f, is evaluated at each of the vertices. The vertices are then moved towards the maximum of f. In each iteration, k, one out of four formulas,

$$\mathbf{P}^{k+1} = g_i(\mathbf{P}^k), \quad i = 1,\ldots,4$$

is used to find the new position of the points $\mathbf{P}$. The moves are made according to certain rules, which ensure that the simplex does never degenerate. The algorithm moves 1 or m points per iteration. It is characteristic of the algorithm that the simplex expands where $f(\mathbf{p})$ is smooth and increasing, and contracts close to the maximum and where the function surface is rugged. Figure 5.1 to 5.7 show the possible moving of vertices in iterations.

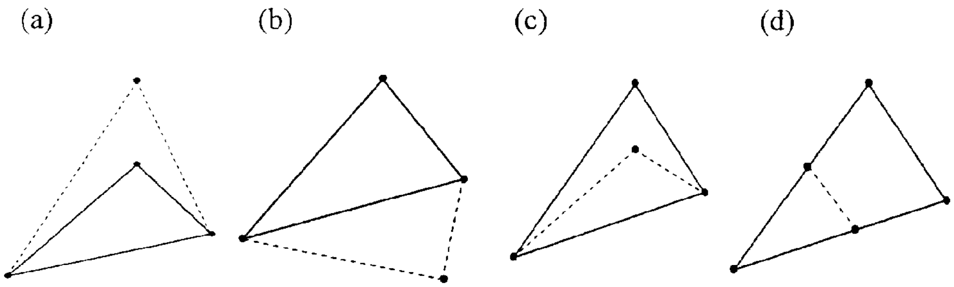

Figure 1. The results of formulas g_i, i=1,...,4 that are used to move vertices of the simplex. The moves are (a) expansion, (b) mirroring, (c) truncating and (d) shrinkage, respectively.

Reparametrization

Elements p_i, i=1,...,m have economic interpretations and are constrained between a lower and an upper limit, $p^{(l)} \le p \le p^{(u)}$. Unconstrained optimisation with respect to $\mathbf{p}$ may give meaningless estimates $\hat{\mathbf{p}}$ that are beyond the limits. However, transformation of the parameters (policy measures) with the reparametrisation by Vold et al. 1999, $\xi(p) = \log((p - p^{(l)})/(p^{(u)} - p))$, ensures that an original parameter p stays within its definition area during unconstrained estimation. Since $e^{\xi} = (p - p^{(l)})/(p^{(u)} - p)$, which is equivalent to $p(e^{\xi} + 1) = e^{\xi} p^{(u)} + p^{(l)}$, we have the unique inverse transformation $p(\xi) = (p^{(u)} e^{\xi} + p^{(l)})/(1 + e^{\xi})$.

Now, we can transform the maximisation problem to

$$\max_{\xi \in R_m} f(\xi)$$

and use an unconstrained optimisation algorithm to find $f(\hat{\xi}) = \max_{\xi \in R_m} f(\xi)$. It is guaranteed then that function evaluations at the final estimate $\hat{\mathbf{p}}(\hat{\xi})$ and at the algorithmic search path are such that the values of the original parameters (policy measures) are within their lower and upper limits.

Policy measures definition area

The lower limits of measures applied were set at zero, whereas the upper limits were set at a large value.

Appendix II

Supplementary results: Social efficiency

In section 7.3, results from the efficiency analyses and all main findings were presented. In this Appendix we present results that are supplementary to the analyses in section 7.3.

Section AII.1-AII.12 contains a brief presentation of the results from simulation of the scenarios. The presentations are based on Table AII.1-AII.12, which correspond to Table 4.3 for presentation of components in the maximised *W* function.

The results from the efficiency analyses in section 7.3.5 show total effects on travel behaviour. Table AII.12 shows corresponding results in terms of percentage changes in travel demand and travel supply for peak and off-peak periods.

AII.1 First-best scenario P11

The total efficiency of the P11 scenario is 868 million EURO (MECU) (Table AII.1). We see that parking operators loose 87 MECU, due to reduced number of car trips and possibly less trips to zones with costly parking charges. The toll revenue collected by the tolling operator is 3630 MECU and the revenue loss on the fuel tax as a consequence of less car use amounts to 430 MECU. External cost savings are 319 MECU. The results in Table AII.1 tell us that total efficiency is 33.8 % of the consumer deficit for the car drivers. In this case the ratio of private timesaving to money losses is 0.38 in the peak period and 0.233 in the off-peak period. External costs other than congestion costs are reduced.

AII.2 First-best scenario S11

The total efficiency of the S11 scenario is 2291 MECU, which shows that the change of the shadow price from zero to 0.25 increases total efficiency of the pricing strategy by a factor of 2.64 for the first-best situation. Parking operators loose 144.4 MECU due to reduced number of car trips and possibly less trips to zones with costly parking charges. The toll revenue collected by the tolling operator is 8370 MECU and the loss on the fuel tax as a consequence of less car use amounts to 999.3 MECU. External cost savings are 592.9 MECU. From this, the main picture is that total efficiency is 39.9 % of the cost for the car drivers, somewhat higher than for the P11 scenario. But the value of the timesaving in the peak period is only 26.9% of the road charge in the peak period and 13.0% in the off-peak period, less than in the P11 scenario.

AII.3 Second-best scenario P21

The overall efficiency gain is 141 MECU. This is only 17.6% of the efficiency gained in the first-best scenario P11. The deficit for car drivers amount to 537 MECU, considerably less than in the "first-best" case. However, total efficiency is only 26.3% of the travellers' deficit. This is lower than in the P11 scenario. In this case the ratio of private timesaving to money losses is 0.37 in the peak period. This is close to that of the P11 scenario. For the off-peak period the same ratio is 1.82, but absolute gains and losses were very small and cannot be considered of significance. The public authority collects 720 MECU of toll revenue and looses 21 MECU in parking fees, plus looses 82 MECU in fuel tax owing to reduced car travel demand. Environmental cost savings in the P2a scenario amount to 60.6 MECU.

AII.4 Second-best scenario S21

The calculated shadow benefit of added public revenue is 681 MECU (one fifth of the net moneysaving for operators and the government). In this case, this benefit amounts to no less than 80 per cent of the total social benefit 644 MECU derived from the pricing scheme. Efficiency in the S21 scenario is 4.56 times that of the P21 scenario. This means that the influence of the shadow price of public funds on total efficiency is considerably greater than for the first-best solution.

In this second-best scenario, car drivers incur a deficit amounting to 2 763 MEuros, i e considerably higher than in the "first-best" case. The public authority collects 3 371 MEuros of toll revenue and 327 MEuros in parking fees, but looses 450 MEuros on the fuel tax owing to reduced car travel demand.

Reduced congestion, in this case, generates time savings worth 739 MEuros. Public transport, on the other hand, obtains a time gain, valued at 68 MEuros. In this scenario, public transport frequency increases by 3.6 per cent in the peak hour and 0.7 per cent in off-peak.

The total efficiency is 23.3 % of the consumer deficit. The ratio of private timesavings to money losses is 0.36 in the peak period and 10.2 % in the off-peak period. The low value in the off-peak period and the fact that the toll policy variable is zero in P21 but 1.338 in S21 indicate that the off-peak toll charges in S21 is a consequence of the shadow price of public funds. Environmental cost savings in S21 scenario amount to 267 MEuro, 4.39 times the savings in P21.

AII.5 Second-best scenario P22

In this scenario the *W*-value is 198 MECU, almost 40 % greater than the *W*-value of the P21 scenario, but still much lower than for the P11 scenario. Car drivers incur a deficit amounting to 2711 MECU. This is much greater than in P21, and slightly more than in the first-best scenario P11. The total efficiency is only 7.3%

of the consumer deficit, much lower than both the P11 and P21 scenarios. This indicates that fuel taxes results in a relatively heavy burden on car drivers if it is used efficiently as a road pricing measure. Reduced congestion in this case generates a time saving worth 463 MECU, and public transport frequency increases by 3.4 % and 0.4 % in peak and off-peak. The value of the private time savings is less than half the monetary consumer deficit. In this case the ratio of private time saving to monetary losses is only about 14.6 %. However the fuel tax produces a large revenue to the government and large environmental cost savings, amounting to 264 MECU.

AII.6 Second-best S22

The *W*-value of the S22 scenario is 9 times and three times the *W*-value of the P22 and S21 scenarios, respectively. This means that the shadow price of public funds has a tremendous effect. If we look at the costs and benefits, we see that car drivers incur large costs in the form of fuel tax outlays (see column "Government and external" in Table AII.6). The value of time savings is only about 12% of the value of the taxes and charges paid. This implies that this scenario is even more "efficient" than S21 in terms of raising revenue. The revenue from the fuel tax is almost ten times the revenue from toll charges, probably because there are close substitutes to trips across the toll ring, but not to car trips in general. The balance between price and the number of travellers who pay is probably still sensitive to the toll charge, i.e. a delicate balance exists, in that the toll charge cannot be set very high without loss of toll revenue. The public transport frequencies are up by 11% and 2 % in peak and off-peak to accommodate the large shifts in mode choice from car to public transport. The shift improves the net result of the public transport companies, and environmental benefits are obtained.

AII.7 Second-best P22b

With the fuel tax, toll charges and parking charges available for optimisation and elastic car ownership, the number of cars in the P22b scenario becomes 3.795e+05 whereas the number of cars in the base scenario is 390522, a 3 % reduction. The number of car trips is reduced more than in P22b in peak (6.34%) and a somewhat greater reduction in off-peak (1.5%). This is probably due to the reduced car ownership.

The W-value of the P22b scenario is 200.1 MECU, only slightly more than in P22. The consumer deficit is the sum of changes in expenditure on cars, +124.5 MECU, the time surplus +553 MECU, and monetary losses –2551 MECU. The private time savings to money losses is then 0.23. The reason for the higher rate in this scenario than in P22 is that fuel taxes cannot be set so high that too many people sell their cars, because this would affect total efficiency by reducing income to the government. Car drivers incur a deficit amounting to 1874 MECU. This is 31% less than in P22, which indicate that a medium-term effect is that people adapt to the new taxes by reducing the consumer deficit, i.e. in the medium-term the car owners decide whether to buy or sell a car on the basis of the taxes. Higher taxes lead to fewer cars, and fewer cars lead to less car trips and less revenue in terms of fuel taxes and annualised car taxes. This interrelationship between the potential reduction in the number of cars and the reduction in revenue lead to a lower fuel tax compared to P22, where car ownership was constant. This implies that there are greater potential time savings left in this scenario that are being realised with higher toll charges in peak.

Public transport frequencies increase by 4.3% and 0.4% in peak and off-peak periods.

AII.8 Second-best S22b

The S22b scenario includes optimisation of the same measures as in S22. In contrast to S22, however, car ownership is adjusted by invocation of the car ownership model. S22 describes the short-term optimal charges whereas S22b describes the medium-term optimal charges. The medium-term optimal charges were found by connecting the car ownership model for calculation of car ownership with respect to the fuel tax. The number of cars in the S22b scenario is 347193 whereas the number of cars in the base scenario is 390522, which is a 13 % reduction.

The *W*-value of the S22b scenario is 50 % higher than the *W*-value of the S21 but 30 % lower than that of S22. If we look at the costs and benefits, we see that car drivers incur large costs in the form of fuel tax (see column "Government and external" in Table AII.8). However, it is less "efficient" than S22 in terms of raising revenue as the value of the timesaving is about 24% of the value of the fuel tax paid. The reason for this is that in the medium-term, car owners decide whether to buy or sell a car on the basis of the taxes. Higher taxes lead to fewer cars, and fewer cars lead to less car trips and less revenue. This interrelationship between the potential reduction in the number of cars and the reduction in revenue lead to lower fuel tax as compared with S22, where car ownership was constant. This implies that there is a greater potential timesaving left in this scenario that is being realised with higher toll charges in peak. Toll charges in peak are slightly higher than in off-peak. The reason for this is that the fuel tax is relatively low, which leaves potential for timesaving, which is greater in peak than in off-peak.

AII.9 Second-best P22c

Like P22b, the P22c scenario is considered medium-term. The number of cars in P22c is 1.904e+05, which is almost 50 % down compared to the base case. This is due to a tremendous increase in annualised car taxes. The number of car trips in the P22c scenario is only 48.8% of the number of car trips in the base case. The average trip length by car increases from 20.04 to 25.78 km in peak and 18.39 to 19.32 km in off-peak. The reason for this is probably that inelastic car trips are much longer than elastic car trips. The overall reduction in car trips is exclusively due to a reduction in the elastic car trips, which is an artefact in the model. The consequence is that the average length of car trips increases. The change in trip lengths for public transport is small. Travel time by car increases from 27.31 to 29.99 in peak periods and is reduced from 21.11 to 20.68 in the off-peak period. This is due to the longer trips.

The optimal toll charge in peak periods for the P22c scenario is zero in both peak and off-peak. The explanation for this is very simple: The great reduction in car trips removes the congestion costs. Hence there is a dead weight loss connected with toll charges and no gains in terms of time savings.

The *W*-value of the P22c scenario is 3381 MECU, far greater than the P11, P21, P22 and P22b scenarios. The reason that the P22c scenario obtains a much larger overall efficiency than the first-best scenario P11 is because the car taxes affects mechanisms that can are not affected by the link-based road pricing.

Car drivers incur a deficit amounting to 4860 MECU. This is large compared with the other scenarios with a shadow price of public funds equal to zero. The consumer deficit is the sum of changes in the expenditure on cars (-6.907e+09 MECU), the time surplus +11364 MECU, and monetary expenses of + 9106. The large expenses of owning a car covers only 70 percent of the extra expenses due to larger car taxes, which are based on the fact that 70 % of the trips are made within the area. We do not calculate the effects of altered car ownership for car drivers representing the inelastic demand, neither consumer surplus nor revenue. But the revenue to the authorities is counted 100%. Hence, if all trips were made within the region, the picture would probably have looked quite different.

The optimal solution in this scenario is undoubtedly influenced by our coarse and inaccurate method of assessing the value of owning a car. It is not to be trusted.

AII.10 Second-best S22c

The W-value of the S22c scenario is higher than the *W* value of any other scenario. If we look at costs and benefits, we see that car drivers incur large costs in the form of time dependent car taxes (see column "Government and external" in Table 6.6). The value of the timesaving is only about 13.2 % of the value of the time dependent car taxes paid and other money expenditures for car drivers.

Time dependent car taxes are almost six times higher than in the base scenario and the fuel tax is lower than in the base scenario. We do not consider this scenario a realistic one. The reasons are the large changes, well outside what can reliably be predicted by the model, and the coarse and unreliable method used to assess the benefits of owning a car, which can be expected to influence the optimum of P22c and S22c appreciably.

Table AII.1 Components of the maximised *W* function (simplified version) for the first-best scenario P11. Economic and financial benefits and costs are net present values in million Euros (relative to base scenario). No shadow price of public funds is applied to changes in the government and local authority budget balances.

	Level of the instruments						
RUN NO.	Parking	Frequency	Road price	Fuel tax	Car tax	Other instruments	
[illegible]	peak/off-peak	peak/off-peak	peak/off-peak	[illegible]	[illegible]	peak/off-peak	
	1.0/1.0	1.040/1.004	0.0/0.0	1.0	1.0	m.c.c.p	
	Travellers		**Operators**			**Government and external**	**Row sum**
Benefit or cost category	Peak trips	Off-peak trips	PT	Parking	Toll		
Investment and operating costs	0.0		0.0	0.0		0.0	
Money savings,road	-2357	-1439		-86.62	3630	-430.3	-682.8
Money savings,PT	0.0	0.0	0.0			0.0	0.0
Financial benefits							
Time savings, road	896.1	335.3					1231
Time savings, PT	0.0	0.0					0.0
Time savings, walk&cycle	0.0	0.0					0.0
External cost savings						319.1	319.1
Total benefit	-2564		0.0	-86.62	3630	-111.2	
W							867.6

Table AII.2. Components of the maximised W function (simplified version) for the first-best scenario S11. Economic and financial benefits and costs are net present values in million Euros (relative to base scenario). A shadow price of public funds of 0.25 is applied to all changes in the government and local authority budget balances, through multiplication of all nominal cash flows by $(1+\lambda)=1.25$, assuming they will have to pay any transport company deficits.

	Level of the instruments						
RUN NO.	Parking	Frequency	Road price	Fuel tax	Car tax	Other instruments	
	peak/off-peak	peak/off-peak	peak/off-peak			peak/off-peak	
	1.0/1.0	1.069/1.008	0.0/0.0	1.0	1.0	m.c.c.p	
	Travellers		**Operators**			**Government and external**	**Row sum**
Benefit or cost category	Peak trips	Off-peak trips	PT	Parking	Toll		
Investment and operating costs	0.0		-171.7	0.0	-0.0	0.0	-171.7
Money savings,road	-3835	-3519		-144.4	8370	-999.3	-126.8
Money savings,PT	0.0	0.0	381.0			0.0	381.0
Financial benefits							
Time savings, road	1033	457.7					1491
Time savings, PT	115.6	9.39					125.0
Time savings, walk&cycle	0.0	0.0					0.0
External cost savings						592.9	592.9
Total benefit	-5737		209.2	-144.4	8370	-406.4	
W							2291

Table AII.3. Components of the maximised *W* function (simplified version) for the first-best scenario P21. Economic and financial benefits and costs are net present values in million Euros (relative to base scenario). No shadow price of public funds is applied to changes in the government and local authority budget balances.

		Level of the instruments						
RUN NO.		Parking	Frequency	Road price	Fuel tax	Car tax	Other instruments	
[illegible]		peak/off-peak	peak/off-peak	peak/off-peak	[illegible]	[illegible]	peak/off-peak	
855		1.025/0.996	1.022/1.001	1.329/0.0	1.0	1.0	None	
		Travellers		**Operators**			**Government and external**	**Row sum**
Benefit or cost category		Peak trips	Off-peak trips	PT	Parking	Toll		
Investment and operating costs		0.0		0.0	0.0	0.0	0.0	
Money savings,road		-855.3	-269.5		-20.79	720.3	-82.01	-240.5
Money savings,PT		0.0	0.0	0.0			0.0	0.0
Financial benefits								0.0
Time savings, road		316.3	491.7					321.2
Time savings, PT		-	-					0.0
Time savings, walk&cycle		0.0	0.0					0.0
External cost savings							60.63	60.63
Total benefit		-536.8		0.0	-20.79	720.3	-21.38	
W								141.3

Table AII.4. Components of the maximised *W* function (full version) for the first-best scenario S21. Economic and financial benefits and costs are net present values in million Euros (relative to base scenario). A shadow price of public funds of 0.25 is applied to all changes in the government and local authority budget balances, through multiplication of all nominal cash flows by $(1+\lambda) = 1.25$, assuming they will have to pay any transport company deficits.

		Level of the instruments						
RUN NO.		Parking	Frequency	Road price	Fuel tax	Car tax	Other instruments	
		peak/off-peak	peak/off-peak	peak/off-peak			Peak/off-peak	
219		1.28/1.62	1.036/1.007	2.11/1.338	1.0	1.0	None	
		Travellers		**Operators**			**Government and external**	**Row sum**
Benefit or cost category		Peak trips	Off-peak trips	PT	Parking	Toll		
Investment and operating costs		0.0		-97.36	0.0	-166.3	0.0	-263.7
Money savings,road		-1449	-2120		327.5	3371	-449.5	-320.3
Money savings,PT		0.0	0.0	154.5			0.0	154.5
Financial benefits								
Time savings, road		521.7	217.0					738.8
Time savings, PT		59.55	8.62					68.17
Time savings, walk&cycle		0.0	0.0					0.0
External cost savings							266.6	266.6
Total benefit		-2763		57.13	327.5	3205	-182.9	
W								644.1

Table AII.5. Components of the maximised *W* function (simplified version) for the first-best scenario P22. Economic and financial benefits and costs are net present values in million Euros (relative to base scenario). No shadow price of public funds is applied to changes in the government and local authority budget balances.

	Level of the instruments						
RUN NO.	Parking	Publ.tran.Freq.	Toll	Fuel tax	Car tax	Other instruments	
	peak/offp	peak/offp	peak/offp			(peak/offp)	
958	1.047/0.934	1.034/1.004	0.8728/0.0	1.403	1.0	None	
	Travellers		**Operators**			**Government and external**	**Row sum**
Benefit or cost category	Peak trips	Off-peak trips	PT	Parking	Toll		
Investment and operating costs	0.0		0.0	0.0	0.0	0.0	0.0
Money savings,road	-1641	-1534		-41.19	480.9	2205	-529.9
Money savings,PT	0.0	0.0	0.0			0.0	0.0
Financial benefits							
Time savings, road	355.9	107.2					463.1
Time savings, PT	0.0	0.0					0.0
Time savings, walk&cycle	0.0	0.0					0.0
External cost savings						264.4	264.4
Total benefit	-2711		0.0	-41.19	480.9	2469	
W							197.6

Table AII.6. Components of the maximised *W* function (full version) for the first-best scenario S22. Economic and financial benefits and costs are net present values in million Euros (relative to base scenario). A shadow price of public funds of 0.25 is applied to all changes in the government and local authority budget balances, through multiplication of all nominal cash flows by $(1+\lambda)=1.25$, assuming they will have to pay any transport company deficits.

	Level of the instruments						
RUN NO.	Parking	Publ.tran.Freq.	Toll	Fuel tax	Car tax	Other instruments	
	peak/offp	peak/offp	peak/offp			(peak/offp)	
333	1.398/1.19	1.112/1.02	1.51/1.103	2.6620	1.0	None	
	Travellers		**Operators**			**Government and external**	**Row sum**
Benefit or cost category	Peak trips	Off-peak trips	PT	Parking	Toll		
Investment and operating costs	0.0		-295.2	0.0	-166.3	0.0	-461.6
Money savings,road	-5181	-7372		86.29	2249	9411	-805.7
Money savings,PT	0.0	0.0	625.1			0.0	625.1
Financial benefits							
Time savings, road	842.1	332.6					1175
Time savings, PT	191.5	24.08					215.6
Time savings, walk&cycle	0.0	0.0					0.0
External cost savings						1058	1058
Total benefit	-11160		329.9	86.29	2083	10470	
W							1806

Table AII.7. Components of the maximised *W* function (simplified version) for the first-best scenario P22b. Economic and financial benefits and costs are net present values in million Euros (relative to base scenario). No shadow price of public funds is applied to changes in the government and local authority budget balances.

	Level of the instruments						
RUN NO.	Parking	Publ.tran.Freq.	Toll	Fuel tax	Car tax	Other instruments	
	peak/offp	peak/offp	peak/offp			peak/offp	
675	0.988/0.929	1.043/1.004	0.996/0.0	1.293	1.0	None	
	Travellers		**Operators**			**Government and external**	**Row sum**
Benefit or cost category	Peak trips	Off-peak trips	PT	Parking	Toll		
Investment and operating costs	124.5		0.0	0.0	0.0	-174.3	-49.86
Money savings,road	-1448	-1103		-82.77	537.9	1567	-529.2
Money savings,PT	0.0	0.0	0.0			0.0	0.0
Financial benefits							
Time savings, road	434.2	118.5					552.7
Time savings, PT	0.0	0.0					0.0
Time savings, walk&cycle	0.0	0.0					0.0
External cost savings						226.5	226.5
Total benefit	-1874		0.0	-82.77	537.9	1619	
W							200.1

Table AII.8. Components of the maximised *W* function (full version) for the first-best scenario S22b. Economic and financial benefits and costs are net present values in million Euros (relative to base scenario). No shadow price of public funds is applied to changes in the government and local authority budget balances.

	Level of the instruments						
RUN NO.	Parking	Publ.tran.Freq.	toll	Fuel tax	Car tax	Other instruments	
	(peak/offp)	(peak/offp)	(peak/offp)			(peak/offp)	
122	1.367/1.455	1.145/1.025	1.726/1.149	2.0148	1.0	None	
	Travellers		Operators			Government and external	Row sum
Benefit or cost category	Peak trips	Off-peak trips	PT	Parking	Toll		
Investment and operating costs	489.1		-377.4	0.0	-166.3	-856.3	-910.9
Money savings,road	-3683	-5350		124.2	2457	5438	-1014
Money savings,PT	0.0	0.0	757.1			0.0	757.1
Financial benefits							
Time savings, road	837.6	386.3					1224
Time savings, PT	248.6	27.34					276.0
Time savings, walk&cycle	0.0	0.0					0.0
External cost savings						937.6	937.6
Total benefit	-7044		379.6	124.2	2290	5520	
W							1270

Table AII.9. Components of the maximised *W* function (simplified version) for the first-best scenario P22c. Economic and financial benefits and costs are net present values in million Euros (relative to base scenario). No shadow price of public funds is applied to changes in the government and local authority budget balances.

		Level of the instruments						
RUN NO.		Parking	Publ.tran.Freq.	Toll	Fuel tax	Car tax	Other instruments	
		(peak/offp)	(peak/offp)	(peak/offp)			(peak/offp)	
753		1.024/1.471	1.268/1.039	0.0/0.0	0.8138	5.264	none	
		Travellers		**Operators**			**Government and external**	**Row sum**
Benefit or cost category		Peak trips	Off-peak trips	PT	Parking	Toll		
Investment and operating costs		-6907		0.0	0.0	0.0	9674	2767
Money savings,road		389.0	521.6		-110.5	0.0	-1951	-1151
Money savings,PT		0.0	0.0	0.0			0.0	0.0
Financial benefits								
Time savings, road		637.8	498.6					1136
Time savings, PT		0.0	0.0					0.0
Time savings, walk&cycle		0.0	0.0					0.0
External cost savings							628.3	628.3
Total benefit		-4860		0.0	-110.5	0.0	8351	
W								3381

Table AII.10. Components of the maximised *W* function (full version) for the first-best scenario S22c. Economic and financial benefits and costs are net present values in million Euros (relative to base scenario). A shadow price of public funds of 0.25 is applied to all changes in the government and local authority budget balances, through multiplication of all nominal cash flows by $\lambda = 0.25$, assuming they will have to pay any transport company deficits.

	Level of the instruments						
RUN NO.	Parking	Publ.tran.Freq.	Toll	Fuel tax	Car tax	Other instruments	
[illegible]	(peak/offp)	(peak/offp)	(peak/offp)			(peak/offp)	
	0.911/1.504	1.345/1.071	1.116/1.283	1.594	4.3	none	
	Travellers		**Operators**			**Government and external**	**Row sum**
Benefit or cost category	Peak trips	Off-peak trips	PT	Parking	Toll		
Investment and operating costs	-4787		-924.5	0.0	-166.3	8381	2503
Money savings,road	-1838	-3914		-294.5	2151	1458	-2438
Money savings,PT	0.0	0.0	1773			0.0	1773
Financial benefits							
Time savings, road	811.8	578.4					1390
Time savings, PT	599.1	91.19					690.3
Time savings, walk&cycle	0.0	0.0					0.0
External cost savings						1349	1349
Total benefit	-8459		848.1	-294.5	1984	11190	
W							5267

Table AII.11. Components of the maximised *W* function (full version) for the first-best scenario P3. Economic and financial benefits and costs are net present values in million Euros (relative to base scenario). No shadow price of public funds is applied to changes in the government and local authority budget balances.

		Level of the instruments						
RUN NO.	Fare	Parking	Publ.tran.Freq.	Toll	Fuel tax	Car tax	Other instruments	
	(peak/offp)	(peak/offp)	(peak/offp)	(peak/offp)			(peak/offp)	
27	0.66/0.66	1.6/1.6	1.084/1.058	0.50/0.50	1.16	0.85	none	
		Travellers		**Operators**			**Government and external**	**Row sum**
Benefit or cost category		Peak trips	Off-peak trips	PT	Parking	Toll		
Investment and operating costs		597.8		0.0	0.0	0.0	-837.2	-239.4
Money savings,road		-1169	-1595		398.3	983.0	757.6	-625.2
Money savings,PT		0.0	0.0	0.0			0.0	0.0
Financial benefits								
Time savings, road		446.0	136.4					582.4
Time savings, PT		0.0	0.0					0.0
Time savings, walk&cycle		0.0	0.0					0.0
External cost savings							200.3	200.3
Total benefit		-1584		0.0	398.3	983.0	120.7	
W								-82.02

Table AII.12. Components of the maximised *W* function (full version) for the first-best scenario S3. Economic and financial benefits and costs are net present values in million Euros (relative to base scenario). A shadow price of public funds of 0.25 is applied to all changes in the government and local authority budget balances, through multiplication of all nominal cash flows by $\lambda = 0.25$, assuming they will have to pay any transport company deficits.

		Level of the instruments						
RUN NO.	Fare	Parking	Publ.tran.Freq.	Toll	Fuel tax	Car tax	Other instruments	
	(peak/offp)	(peak/offp)	(peak/offp)	(peak/offp)			(peak/offp)	
	0.66/0.66	1.6/1.6	1.084/1.058	0.50/0.50	1.160	0.85	none	
		Travellers		**Operators**			**Government and external**	**Row sum**
Benefit or cost category		Peak trips	Off-peak trips	PT	Parking	Toll		
Investment and operating costs		597.8		-310.9	0.0	-166.3	-1047	-926.0
Money savings,road		-1169	-1595		497.9	1229	947.0	-90.50
Money savings,PT		725.1	299.4	-792.3			0.0	232.3
Financial benefits								
Time savings, road		446.0	136.4					582.4
Time savings, PT		139.8	61.34					201.1
Time savings, walk&cycle		0.0	0.0					0.0
External cost savings							200.3	200.3
Total benefit		-358.4		-1103	497.9	1062	100.8	
W								199.5

Table AII.13. Some quantities characterising travel demand and travel supply of the peak and off-peak periods of the base scenario and percentage changes for the alternative scenarios relative to the base scenario.

(peak/off-peak)	base case	P11	S11	P21	S21	P22	S22	P22b	S22b	P22c	S22c	P3/S3
Car trips	399 165/646 407	-5.57/-1.11	-9.88/-2.67	-3.08/0.00	-5.38/-2.00	-4.99/-1.13	-16.7/-6.11	-6.34/-1.54	-21.2/-7.45	-36.6/-11.3	-46.8/-15.7	-7.31/-1.21
PT trips	226 188/103 350	7.8/0.7	13.50/1.46	3.86/0.16	6.66/1.27	6.39/0.62	21.69/3.78	8.21/0.72	27.79/4.39	49.96/6.88	63.53/12.4	16.28/10.4
W/B trips	102 302/77 619	4.5/0.4	8.69/1.09	3.51/-0.16	6.26/0.96	5.33/0.28	17.29/3.02	6.57/0.40	21.37/3.53	32.45/4.79	42.25/8.66	-7.49/-8.37
Car trip times (min)	27.31/21.1	-17.5/-5.83	-20.3/-9.03	-5.97/-0.05	-9.73/-5.89	-7.13/-3.72	-17.7/-16.2	-7.39/-2.80	-13.4/-12.9	9.80/-2.04	6.16/-11.37	-5.75/-3.86
PT trip times (min)	48.8/50.8	0.08/0.06	0.74/-0.02	-0.89/0.07	-1.48/-0.13	-0.05/0.05	1.06/-0.06	-0.33/0.01	-0.37/-0.36	-1.81/-1.10	-1.08/-1.60	1.52/0.92
W/B trip times (min)	103.0/148.1	0.32/-0.38	2.85/-0.69	-1.91/-0.07	-3.25/-0.83	0.85/-0.22	7.27/-0.86	0.29/-0.33	3.91/-1.68	4.51/-2.86	10.29/-3.73	-8.46/-0.78
Car trip distance (km)	20.04/18.4	-2.25/-3.5	-3.04/-7.14	0.24/0.06	1.24/-3.38	-0.74/-3.15	-1.34/-15.1	1.45/-2.29	4.73/-10.19	28.63/5.02	29.33/-5.39	3.89/-2.48
PT trip distance (km)	16.27/14.7	0.1/0.6	1.56/-0.21	-0.67/0.17	-1.46/0.08	0.53/0.01	2.56/-0.36	0.11/-0.28	1.46/-0.39	2.01/-0.28	3.63/-0.78	4.14/2.95
W/B trip distance (km)	8.58/12.3	0.32/-0.38	2.85/-0.69	-1.91/-0.07	-3.25/-0.83	0.86/-0.22	7.27/-0.86	0.29/-0.33	3.91/-1.68	4.51/-2.86	10.29/-3.73	-8.46/-0.78
Car ownership	390 522	0	0.	0	0	0	0	-2.827241	-11.1	-51.2	-51.5	1.69